Optimal use of Rainwater Tanks to Minimize Residential Water Consumption

A thesis submitted in fulfilment of the requirements for the degree of Masters of Engineering

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DECLARATION

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; and, any editorial work, paid or unpaid, carried out by a third party is acknowledged.

Anirban Khastagir

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ABBREVIATION

A	Roof area connected to the tank (m^2)
ARC	Average residential consumption (KL/person/year)
ARD	Total average residential daily water demand (ML/Day)
C	Tank Capacity (kL)
C_R	Co-efficient of runoff
CWW	City West Water
D	Annual water demand (kL/Year)
D_t	Demand for rainwater (Usage)
E	Coefficient of Efficiency
G	Garden watering
I_{eff}	Daily effective rainfall (mm)
L	Laundry use
LPCD	Litre per capita per day
MAR	Mean annual rainfall (mm)
MDR	Mean Daily rainfall (mm)
M_t	Mains water use (kL)
N	Total number of days
NRP	Number of residential property
P	Number of days the tank is not empty
Q_t	Runoff from the roof into the tank on the t^{th} day (kL)
R^2	Coefficient of Determination
RD	Total demand for mains water
Re	Probability of the tank being not empty as a percentage
RWS	Residential water supply (ML/year)
S_t	Storage value at the beginning of t^{th} day (kL)
S_{t+1}	Storage volume in the tank at the end of t^{th} day (kL)
SEW	South East Water
T	Toilet flushing
t	Time period (h)
TN	Total Nitrogen
TP	Total Phosphorus
TSS	Total Suspended Solid

WSE	Water saving efficiency (%)
WSUD	Water Sensitive Urban Design
YVW	Yarra Valley water
Π	Dimensionless variables

Abstract

Melbourne, the capital of Victoria Australia leads the world in having the highest quality drinking water. Similar to other developed capital cities in the world, it has to confront a growing water demand due to population increase and economic development. In addition, Melbourne had currently in a severe drought facing its twelfth consecutive below average rainfall year. The Victorian State Government has set targets for reducing per capita water consumption by 15%, 25% and 30% by 2010, 2015 and 2020 respectively and has announced stringent water restrictions to curtail water demand. In this resource constraint environment it is opportune to look for alternative sources of water to supplement Melbourne's traditional water supply.

In Melbourne, legislation has been changed to make it possible to use rainwater harvested from domestic tanks for non potable purposes. Rainwater tanks may also protect urban streams by reducing stormwater runoff, delaying peak flows and trapping pollutants from reaching downstream waterways. The annual rainfall in Melbourne's metropolitan area varies from 450mm in the West to 850mm in the East to over 1000mm in the North East mountain ranges.

The objectives of the current study are to develop a methodology to estimate the optimal size of the rainwater tank at a particular location considering the local rainfall, roof area, demand for water and the reliability of supply (supply security) required; to quantify the rainwater volume that could be harvested at site using domestic rainwater tanks to minimise pressure on the potable water supply secured from traditional catchment sources until the desalination plant is commissioned in 2013; to analyse the efficacy of rainwater tanks to reduce the stormwater runoff and improve the quality of the stormwater that will otherwise flow into urban drains and to estimate the cost effectiveness ratio and payback period of installing rainwater tanks.

A simple water balance model was developed to calculate the tank size based on daily rainfall, roof area and the expected demand. The concept of 'reliability' was introduced to measure supply security. Rainfall data from 20 rainfall stations scattered around Melbourne were used to determine the variation in the rainwater tank size dependent on the above stated parameters. In addition, the study presents a reliability centred methodology and the results of the variation in tank sizes required to meet a similar demand across metropolitan Melbourne (due to the spatial variability of rainfall across the Greater Melbourne area). It was observed that to achieve the same supply reliability (90%) and to meet a specific demand (toilet and garden use), the tank size required in the western side of Melbourne is as high as 7 times as that required in the north-east side. As a result, the "one size fits all" approach is

not applicable in Melbourne considering the spatial distribution of mean annual rainfall (MAR). However, a number of curves were required for the different rainfall stations to optimize the rainwater tank size based on MAR, roof area and the demand for rainwater use. In this study, a unique generalized curve was developed to determine the optimum tank size considering the variation in MAR, demand, roof area and supply reliability. By using the generalized curve it was observed that in low rainfall areas (MAR < 550mm/year) rainwater can be used for toilet and garden use only with a reasonable reliability (85% and above). However, in high rainfall areas (MAR > 850mm/year) it is possible to achieve any demand and supply reliability by using a 5kL rainwater tank. The generalised curve provides future opportunities to develop web-based tools for customised tank selection across the Greater Melbourne area. The derived methodology is also applicable to other capital cities in Australia.

The 20 rainfall stations of Greater Melbourne were divided into three water zones based on the three water retailers in Melbourne (Yarra Valley Water, South East Water and City West Water) to calculate the percentage reduction of potable water supply in these above stated water zones over the next 5 years until the desalination plant is commissioned in 2013. The study demonstrated that if every household of Melbourne installed a 3kL rainwater tank for non potable purposes, the annual potable reticulated water savings will be between 16% to 24% in the above stated zones. The impact of less than 100% tank penetration could be computed by adjusting the above result proportionately. Providing financial incentives to encourage Melburnians to actively participate in rainwater harvesting programs will assist the movement towards achieving the Victorian State Government water conservation targets.

In Melbourne, rainwater is currently limited to non potable use, which does not require good quality water. However, the quality of rainwater collected in rainwater tanks depends considerably on the maintenance of the tank and the roof, and how one treats the first flush. The MUSIC model was used in this study to determine the impact on Total suspended solid (TSS), Total Phosphorus (TP), Total Nitrogen (TN) and stormwater runoff that will be prevented from flowing into urban drains due to installation of rainwater tanks. The study demonstrated that there is considerable improvement in stormwater quality improvements due to rainwater stored in the tank. This percentage reduction was distinctly visible for flow (13% to 75%) and TN (72% to 80%). Irrespective of tank sizes used and the demand for the water the percentage reduction in TSS was more than 90%.

Finally, the cost effectiveness of using rainwater for nonpotable domestic use in comparison with traditional reticulated water supply was analysed and showed that the payback period for a 5 kL rainwater tank in the Kinglake area (MAR = 1050mm) with a discount rate of 10%

was around 14 years. The payback period varies most with the tank size which dominating the cost. This demonstrates that the selection of the tank size is the most important factor to ensure maximum use of rainwater and the maximum financial return from the initial capital investment.

Chapter 1

1.1 Motivation

Melbourne, Australia (Figure 1-1) is one of the most 'Liveable' cities in the world and is renowned for having reliable high quality drinking water. However, similar to other developed cities in the world, it has to confront growing water demand due to ever increasing population and continuous economic development whilst the available resources continue to diminish due to dramatic climate change (Melbourne Water 2001). On top of this, Melbourne is facing a severe drought having its twelfth consecutive below average rainfall year. In response to Melbourne's Water Resources Strategy (Melbourne Water 2001), the Government released its *'Our Water Our Future'* policy document setting a target of reducing per capita water consumption by 15% by 2010 (Department of Sustainability and Environment, DSE 2006). Responding to sever persistent drought, the Government further stretched the water conservation target by increasing the 15% to 25% and 30% by 2015 and 2020 respectively (Department of Sustainability and Environment, DSE 2006).

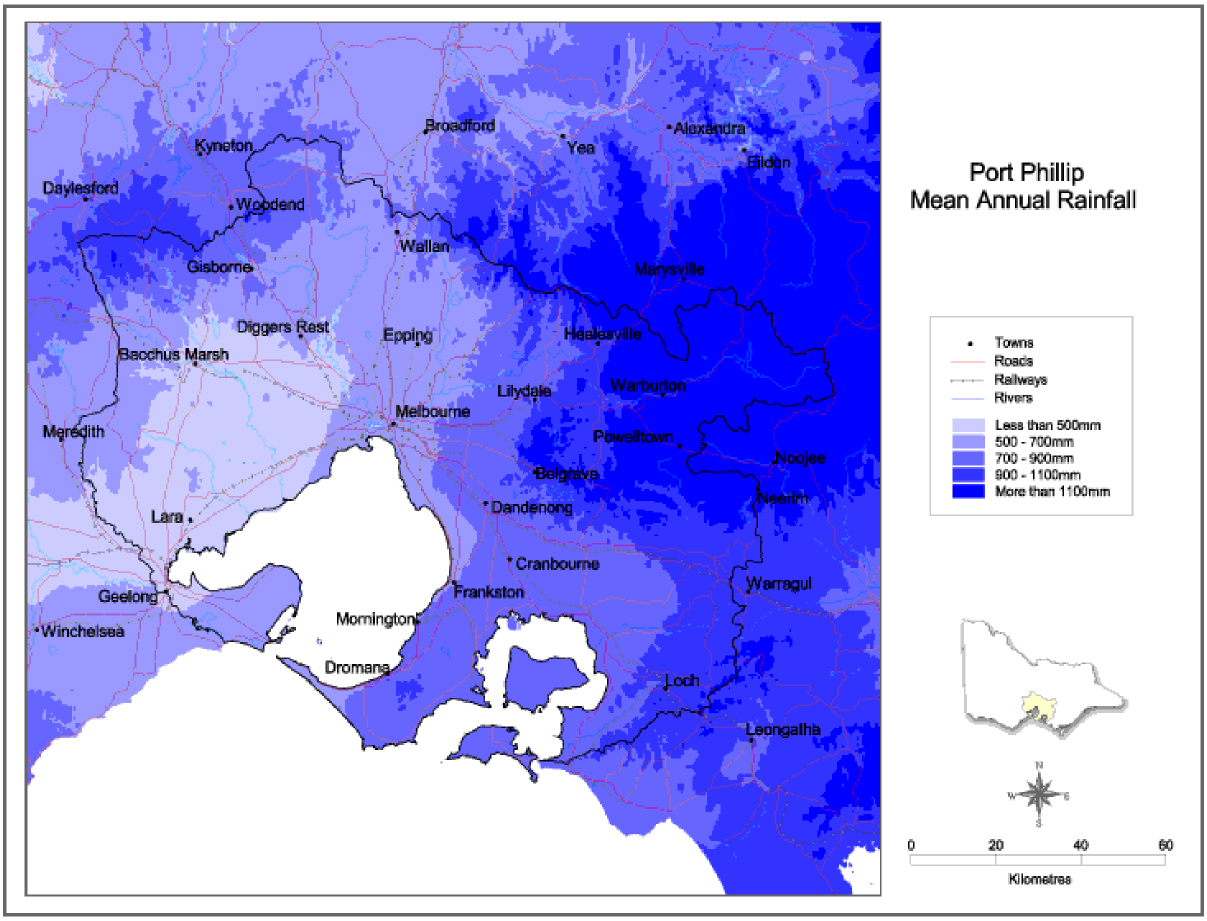

Figure 1-1: Map of Greater Melbourne (DPI 2008)

It is a matter of great concern that in Melbourne less than 2% of mains water supply is used for potable purposes although large proportion of mains water is used for other purposes which do not require water of potable standard (ABS 1994). Majority of water consumption in urban cities is for outdoor use, hot water and for toilet flushing (Coombes et al, 2002). Currently, many householders are showing interest in using rainwater as an alternative source of water even in areas receiving mains water. New water restrictions implemented from 01 September 2006 and announced infrastructure augmentation projects would help securing Melbourne's water supply for the next 50 years and beyond (Our Water Our Future, 2006). In Victoria the use of domestic rainwater tanks is an established and relatively common practice, particularly in rural and remote areas. Between 1994 and 2001, 13 % of Victoria households using rainwater tanks, with 11% of them used rainwater as their prime drinking water source (ABS 1994). Furthermore, rainwater tanks were widely used in non capital city areas (36%) in comparison with capital cities (3%), the study noted.

In September, 2001 the Victorian Government declared that town planing (except in heritage zones) approvals were not required throughout Victoria for the installation of rainwater tanks up to 4,500 litres capacity (Urban Rainwater Systems, 2007). The study also noted that Victorian legislation conferred legal rights to property owners to use rainwater. Amendments to the Water Act, 1989 (passed in April, 2002), explicitly provide for property owners' continued rights to the unrestricted use of rainwater for domestic purposes on their property free of charge. The benefits of rain water are maximised if it is used for toilet flushing, garden watering and for laundry (non potable purpose) because these uses do not need water of good quality (potable substitution). Victorian Government policy was to support the use of rainwater tanks and provide financial incentives for potable substitution whilst meeting the Department of Human Services public health guidelines and the Plumbing Industry regulations.

The water from the tanks can be used for garden use, toilet flushing, washing clothes and in the hot water systems. This constitutes about 80% of the water consumed within a residential property (Melbourne Water 2006). Currently, the whole of the Greater Melbourne area is treated meteorologically and hydrologically as one homogeneous entity. A house owner who is a potential customer for a rainwater tank has no guidelines that he could use to customize the size of a rainwater tank other than the area available to locate it within his property, the aesthetic issues surrounding it and the money he is willing to spend for the tank. The most important aspect of the tank is the level of service that this tank could provide reliably and thus, there are a number of other variables that are more important effecting the decision. These include (i) the rainfall in the area, (ii) the extent of the catchment (roof area) and (iii) the type of planned end use for the water. As a result, it is expected that under favourable conditions (high rainfall, large roof area and lower demand) a tank system will be capable to fulfil all or most of the in-house demand. Unfortunately there are no set guidelines (or a handbook) currently to select the optimum size of the rainwater tank depending on the rainfall in the locality, the roof size and the demand for domestic use. The Water Sensitive Urban Design Manual (2005) provides guidelines when selecting tank sizes based on mean annual rainfall, roof area, roof water demand for toilet use and supply reliability for three different hydrological regions in Victoria. This gross approximation is marginally important to 'no information at all' but is still considered inadequate.

It is evident that the 'one size fits all' philosophy is unsatisfactory when one examines the rainfall characteristics within the Greater Melbourne Area. The mean annual rainfall varies with location. For example, the rainfall is around 450mm/year in the west, 750mm/year in the east and 1050 mm/year in the north east. For example, 3 kL tank would provide different levels of reliability in the three above stated areas. The main objective of this research is to develop a simple set of guidelines to select the optimum rainwater tank size for domestic use depending on the annual rainfall of the location, demand for rainwater use and the catchment size (roof area) to deliver preset supply reliability. The decision related to determining the size of the rainwater tank to be installed in ones property is ultimately a compromise between maximising the use of the rainwater, the reliability of meeting the demand throughout the calendar year, the cost of installing a rainwater tank and the space available in a property to locate the tank.

1.2 Scope

This research aims to assess the possibility of meeting a part of the growing residential water demand in Melbourne with alternative sources of water using rain water tanks. The study plans to develop a tool to determine the optimum size of a customised rainwater tank by investigating the reliability of the tank to meet the demand based on the geographic location of the house, the area draining to the tank (catchment) the number of occupants in the house, the type of appliances used, the garden size and the dominating vegetation. In developing the tool the spatial variability of rainfall over the whole of Greater Melbourne will be considered. It is also planned to determine the efficacy of rainwater tank as a potential water sensitive urban design component. In addition it was also decided to look into the water quality aspects and the cost of rainwater tanks which are equally important aspects when considerations are given to installing a rainwater tank.

1.3 Objectives

The objectives of this research are to:

- Quantify the volume of water that could be harvested by stormwater using rainwater tanks minimising the pressure on the traditional mains potable water supply
- Optimize the size of the rainwater tanks to maximize the use of rainwater harvesting opportunities at a particular location. This will maximize return to the consumer for investing in the rainwater tank.
- Determine the ability of rainwater tanks to meet the challenges set by Melbourne's Water Resources Strategy report for the three retailer water companies operating in Melbourne.
- Analyse the efficacy of rainwater tanks to reduce the stormwater runoff and quality of the stormwater that will otherwise flow into urban drains.
- Carry out a cost-effectiveness analysis that will help the potential tank user to select the most cost effective rainwater tank.

1.4 Possible outcomes of this research

The prime contributions of this research are to:

- Improve the overall perception about the significance of determining the optimum rainwater tank size for domestic dwellings for the Greater Melbourne area.
- Estimate of the volume of water savings required over and above what is produced by harvesting rainwater to meet future more stringent water conservation targets set for the Greater Melbourne area.
- Carry out an analysis to determine the effectiveness of rainwater tanks to facilitate stormwater quality improvement (by storing rainwater in the tank) by reducing the percentage of stormwater flow volume, Total Suspended Solid (TSS), Total Phosphorus (TP) and Total Nitrogen (TN).
- Carry out an analysis of predicting the most cost-effective tank for residential use. This analysis will be carried out in different geographical areas to maximise residential stormwater use and minimize cost.

1.5 Layout of the thesis

This thesis is divided into eight chapters. Detailed appendices are provided at the end of the thesis presenting all the comprehensive graphs as well as a list of conference papers published in relation to this research. The thesis chapters are briefly discussed next.

Chapter 1 illustrates a concise overview of this research and the significant outcomes expected from this thesis. Chapter 2 evaluates and reviews some of the prior and contemporary literature in the form of studies, models, methodologies and publications of domestic rainwater tank harvesting systems in relation with this present study in Australia as well as in different overseas countries. Chapter 3 presents the developed water balance model used to show the variation in tank size across Greater Melbourne. Chapter 4 illustrates the development of the methodology to calculate the optimum rainwater tank size. Chapter 5 presents simulation results carried out to quantify the impact of rainwater tanks in managing residential water demand in Greater Melbourne. This will help to determine the role that tank could play to meet the challenges set by Victorian Government in “Water Resources Strategy report” to save water. Chapter 6 discuses the issues related to water quality aspect of rainwater tank through summarizing findings from different contemporary literature reviews of studies carried out by other researchers. In addition, the Chapter will also analyse the efficacy of rainwater tank as a potential water sensitive urban design component to reduce flow volume, TSS, TP and TN. Chapter 7 carries out a cost–effectiveness analysis in order to estimate the payback period, cost effectiveness ratio and levelized cost of installing a rainwater tank in different parts of Melbourne. Chapter 8 presents the summary, and conclusions of this study.

Chapter 2
Literature Review

2.1 Introduction

This chapter will focus on reviewing the relevant literature on the current and future water demand and supply situation in Greater Melbourne, receptiveness of rainwater use, available rainwater tank models and the use of rainwater tanks as a supplementary source of reticulated water supply. Through this literature review, the key characteristics involving rain water tanks, namely optimum tank sizing and potable supply savings will be reviewed and areas identified for further research described.

2.2 Significance of alternative water source

Birell et al (2005) estimated that domestic water consumption would increase by 33% to 42% across Melbourne by 2031. This estimation was based on a number of factors such as: continuos increase of single occupancy dwelling, implementation of urban consolidation policies and population growth projections. Urban population is increasing rapidly and thus dramatically increasing the demand for potable water. Besides this, Melbourne is now in the 11th consecutive years of drought which makes the situation worse. Melburnians are currently complying with Stage 3a water restrictions which limit outdoor water use. As a result, the policy makers have announced a number of augmentation options as well as water conservation measures and the use of alternative supply sources with a view to proving a supplementary source of water. Alternative water sources and associated technologies have attracted importance over the last 3 to 4 years resulting in further water policy development. As a result, significant discussions are going on to substitute potable water supply with alternative sources such as: fit for purpose stormwater, grey water, rainwater and groundwater (Clarke and Brown 2006). However, the success of these alternative sources depends on the level of receptiveness (from a social point of view that they are implemented. (Jeffery and Seaton 2004). Po et al (2004) observed that the inadequacy of the quantum of social research influencing the community receptiveness and behavioural changes directly relate to use of alternative supply sources. Syme et al (2000) noted the inefficiency and ineffectiveness of some 'save water campaigns' specially designed to promote domestic water conservation.

Climate change predictions for Melbourne from 2020 to 2050 carried out by Howe et al (2005) concluded that average annual temperature would increase by 0.3 °C to 1.0°C by 2020 and

0.6°C to 2.5°C by 2050. Furthermore, rainfall would reduce drastically with models suggesting annual average precipitation changes of -5 to 0% by 2020 and -13 to +1% by 2050. In addition, there is every possibility of witnessing extreme and unprecedented events for examples: more hot days, more dry days and higher rainfall intensities during storm events. The study also postulated that average long-term stream flows potentially would reduce between 3% and 11% by 2020, and as much as 7% to 35% by 2050. The study also revealed unless augmented, water demand in Melbourne would be equal to supply by 2020. Hence, it is important that we investigate some alternative sources of water supply to help ease issues associated with future water scarcity.

Neil et al (2001) reported the importance of achieving sustainable potable water use by reducing per capita consumption to reduce pressure on available potable water. On the other hand, Mitchell (2004) noted that it is a must that integrated urban water management as well as water solutions be developed and nurtured alongside the planning and implementation of infrastructure projects to augment supply. The study also found that a system which would be cost effective and acceptable to users could be successfully integrated to implement urban water management approaches. Introduction of rain water tanks can be stated as an effective way of mitigating storm water impacts, conserving potable water and hence utilization of otherwise a wasted resource. However, the study concluded that to be effective rainwater tanks ought to be connected to substitute mains water supply.

Clarke and Brown (2006) carried out a survey result on the use of alternative water sources in the supply area covered by the city of Bayside, in Southeast Melbourne. They noted that about 52% of respondents installed water-efficient showerheads in their homes which was a sign of their commitment to conserving water. Further, 6% of the respondents had installed rainwater tanks and a further 5% of them had installed grey water reuse systems. The authors noted that the major barrier to the installation of rainwater tanks was the inadequate guidelines for installing and selecting tank. Furthermore, some of the respondents were reluctant to install a rainwater tank because of the perceived high costs, uncertain benefits and the complexity involved in installing a tank.

Collins and Davies (2004) stated that the community was affected by issues such as water restrictions. Recent increased environmental awareness and the persistent drought have combined to influence people to take up water saving rebates and install rainwater tanks, the study observed. However, the rebate schemes and current legislation and codes not incapable in making rain water tank installations cost-effective. The study also reported on the importance of other water conservation initiatives together with rainwater tanks. Although on some occasions, water supply catchments were not receiving sufficient rainfall some urban areas continued to receive heavy rainfall. Hence, it is practical to consider utilising the roof areas of the catchments (houses) for collecting and retaining water for non potable use. This will help to reduce the mains supplied water to houses and hence reduce the demand on water supplied from dams. The water saved in the dams would go towards increasing supply reliability.

Coombes et al (2000) verified that using rain water tanks for supplying outdoor, hot water and toilet flushing in the Lower Hunter region can reduce annual water demand up to 24,700 ML. They also demonstrated that construction of some new infrastructure could be postponed for as long as 34 years if rain water tanks are introduced.

Mitchell and White (2003) explained the efficacy of separately planning water, sewage and stormwater systems. By using this system it was possible to reduce residential use by 45 liters per capita per day (Lpcd). The study also reported that by using rain water in the hot water system the demand could be reduced by 44 lpcd in Melbourne's northern suburbs.

2.3 A review of current practice

Rain water harvesting is considered to be a traditional practice in some countries. Rainwater harvesting for domestic use is a popular topic among the researchers who are identifying key issues that need to be addressed to promote it worldwide looking back at the historical development of the use of rainwater tanks. Gould (1999) referred to the first conference on the use of rainwater systems for domestic water supply in Honolulu, Hawaii in 1982 where 50 academic and practitioners were present. It was the beginning of a series of international conferences on rainwater harvesting where thousands of participants were present from a very broad cross-section of countries, professions and advocacy bodies.

Australia is generally known for its dry arid climate and hence, pure potable water is a precious commodity in many parts of the country. The concept of rainwater harvesting is quite an accepted concept in rural Australia. This practice was initiated more than 25 years ago in Australia. ABS (2001) reported that more than 90% of Australians completely depend on domestic supply from reticulated mains. On the contrary, there are still huge areas with very low population densities with few or no reticulated supplies where rainwater tanks are used ABS (2001) noted that 16 % of Australian households used rainwater tanks, with 13 % of households using tanks as their main source of drinking water between 1994 -2001. The 2001 ABS survey found that 83 % of households with rainwater tanks considered the volume of water supplied by rainwater were sufficient for their needs. Melbourne, one of the capital cities of Australia is suffering from acute water shortages due to drought, continuous population growth and possible climate change effects. On top of this, the current Government policy is not to build new dams and hence Melburnians have to manage within the available resources until the sugarloaf interconnecter and the desalination plant are commissioned in 2010 & 2012 respectively. Water restrictions implemented from 1st September 2006 demonstrate the severity of the current situation. More stringent water conservation targets are set for 2015 and 2020 (Department of Sustainability and Environment, 2006).

Stormwater (2007) revealed that the NSW government was taking some adequate steps with a view to making the installation of large rainwater tanks easier. The report also stated the government's future plan to amend special environmental planning policy no. 4 whose main objective was to double the permissible maximum size of a rainwater tank on a property to be as big as 10 kL. The report also presented the speech of the former NSW premier Mr. Bob Carr who supported installing rainwater tanks because it would save up to 37% potable water if installed widely across NSW. The NSW Minister for Energy Mr Kim Yeadon also stated that Sydney Water would do free installation of new water meters with a backflow device which would stop the water from the tanks entering the reticulated supply. The minister also emphasized the importance of a rebate scheme which would ensure a discount on purchase value of rainwater tanks to make people more interested in installing these.

Joliffe (1997) stated that there were numerous ways through which rainwater tanks could be configured, ranging from corrugated or concrete tanks (commonly used in rural parts of Queensland). In addition, McAlister (1999) stated that in many parts of Queensland rainwater was the only source of water and used concurrently for potable and non potable purposes. He also observed that the people of Queensland were inclined to use rain water in parallel with reticulated water and they also used rain water for drinking purposes.

White (1998) stated that the use of water from rainwater tanks as a possible solution of watering gardens could reduce 25% of mains water used. The above author reported an example of a project on rainwater tanks. He also carried out the cost benefit analysis in that project. During this project it was assumed that the capital cost of reinforced concrete tanks could be amortized if proper maintenance work could be ensured. The rainfall in that area was 1880 mm/annum and average annual supply from rainwater tanks of manifold sizes (5kL – 45 kL) and different tank material (Galvanized iron and Reinforced Concrete) were measured. The study also argued that the cost of water had to increase up to $ 2.2/kL for roof water to match the cost of reticulated supply for household purposes. The study also explained that the reliability of rainwater was completely dependent on the:

- Catchment area
- Pattern of rainfall and intensity
- Water demand; and
- Capacity of tank

One of the major concerns of rainwater harvesting is the alleged apprehension about the water quality of the stored water in the tank. Coombes et al (2000) reported that an improvement in harvested water quality could be ensured through an integrated system treatment which included hot water systems, yielding water with a quality compliant with Australian Drinking Water Guidelines. Heavy metal concentrations in the sediment in rainwater tanks exceed Victorian EPA guidelines (EPA Victoria, 2004) and may become a source of metal pollution within the tank (Magyar et al., 2007).

Abbott et al (2007) stated that inappropriate maintenance facilities, insufficient purification of the water, improper designed delivery systems and storage tanks, and incapability to adopt physical measures to safeguard the water against microbiological contamination are the prime reasons of occurrence of any possible faecal contamination in rain water. On the contrary, Coombes (2002) illustrated that presence of any coliforms could not be used as a vital sign of contamination in rainwater. The study argued that coliforms could occur very naturally in the environment. The prime sources of the faecal contamination were faecal material deposited by birds, frogs, dead animals and insects, either on the roofs or in the water tank itself (Duncan and Wight 1991). The use of protective measures and equipments can significantly improve the water quality because tank fitted with the first flush diverter consistently yielded low to zero total coliforms and E colis.

2.3.1 Current guidelines for selection of tank size

The most significant aspects of rainwater harvesting is the selection of the appropriate rainwater tank size. Water Sensitive Urban Design (WSUD 2005) provides guidelines for rainwater tank sizing for Victoria. These guidelines were developed assuming that rainwater would only be used only for toilet flushing. Different sets of guidelines were developed for Southern, Northern and Central Victoria. Within these areas rainfall was expected to be non–variable. Figure 2.1 depicts the guidelines in WSUD. In addition, Figure 2.2 depicts specific guidelines for southern Victoria.

Nonetheless, the use of these guidelines are limited if a potential tank user wants to use the harvested rainwater for outdoor use as well as for indoor use other than flushing toilets (eg. laundry use). In addition, the Government's present rebate scheme (reported in Chapter 5) encourages the people to use rainwater for both indoor and outdoor use. Furthermore, rainfall variability within the geographic area (eg Southern Victoria) has not been considered when developing the WSUD guidelines. As a result, it is concluded that for selecting the tank size taking maximum rainwater use is required for the Greater Melbourne area.

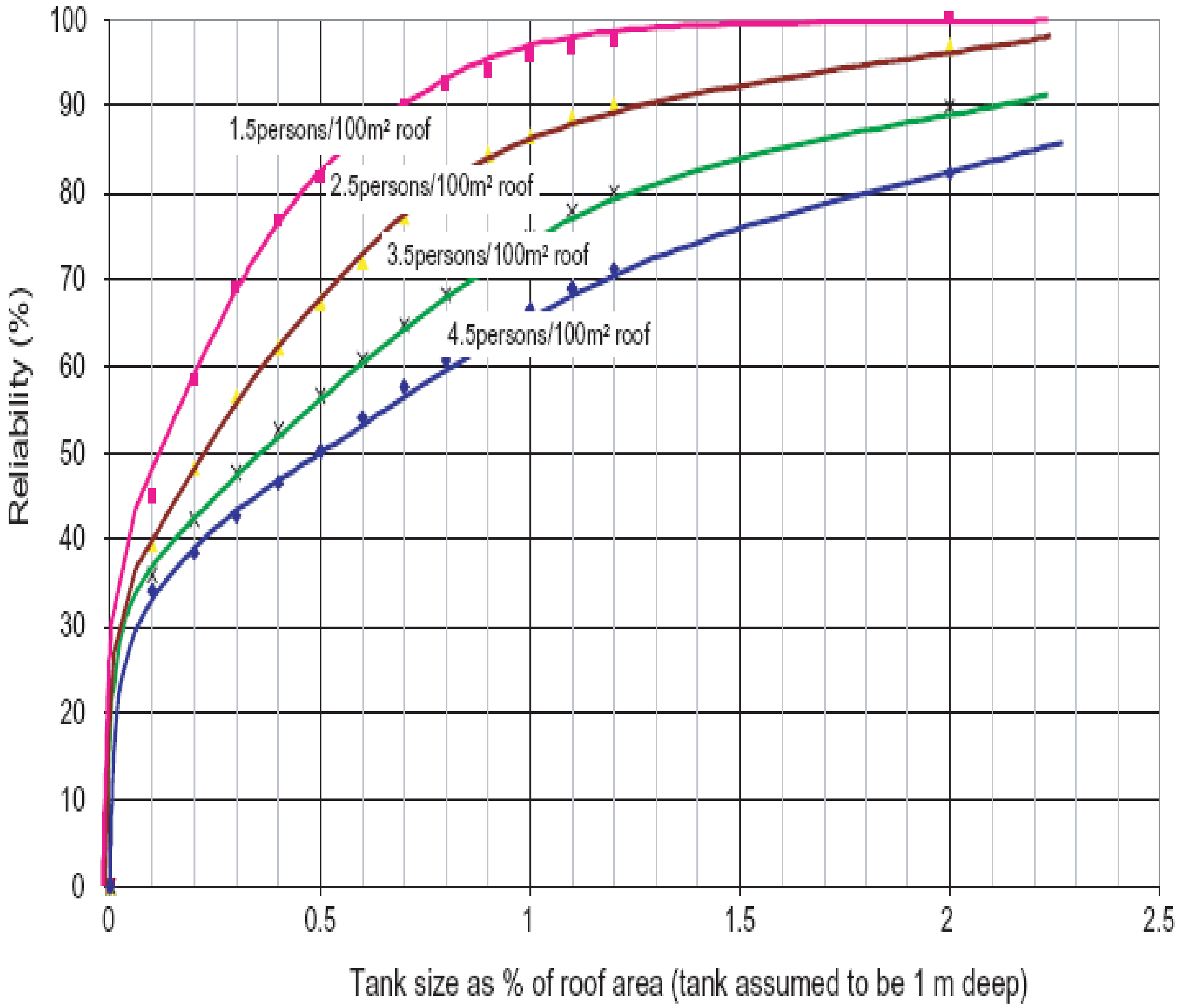

Figure 2.1 WSUD guidelines for selection of tank size for different parts of Melbourne (WSUD, 2005)

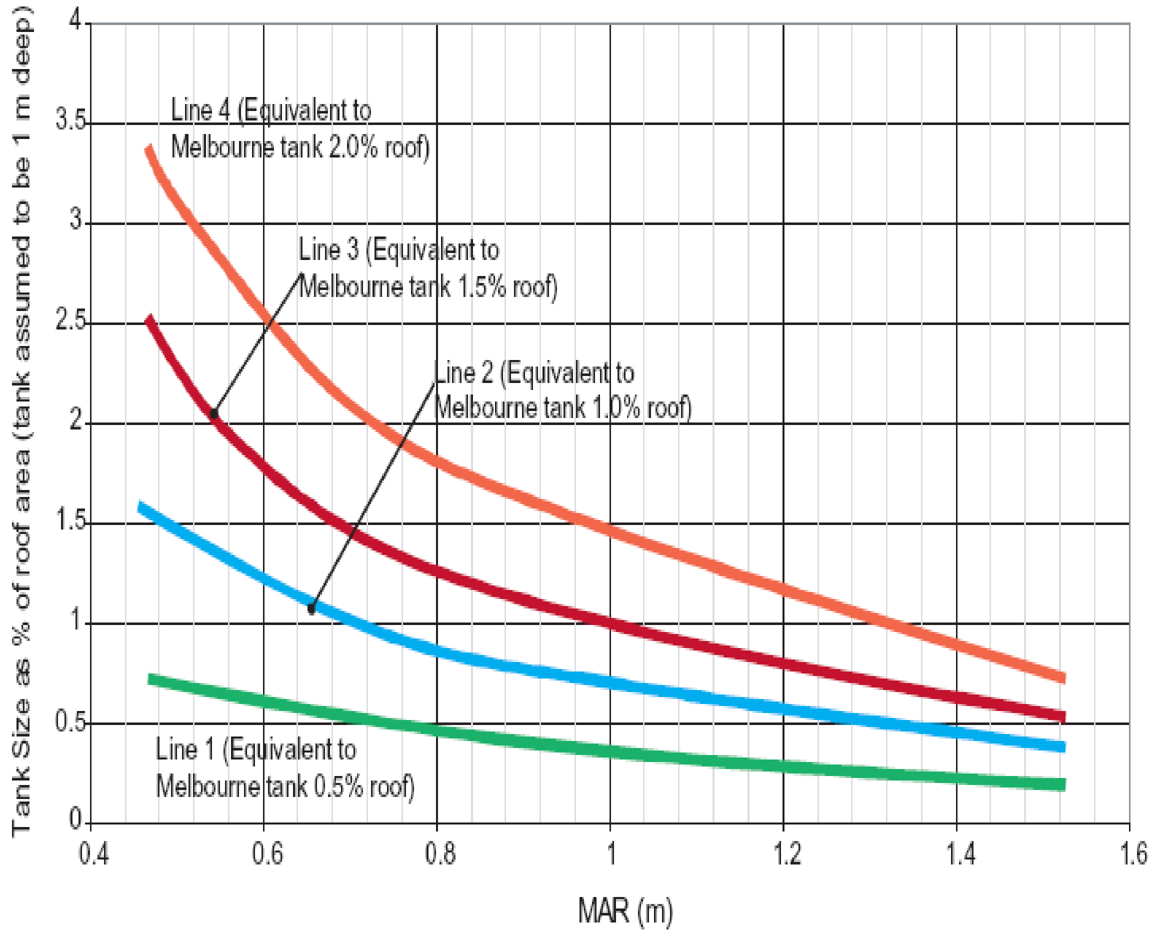

Figure 2.2: Variation in tank sizes due to variation in mean annual rainfall (Southern region) (WSUD, 2005) [MAR = Mean Annual Rainfall]

Duncan and Wight (1991) reported on the selection of rainwater tanks for domestic water supply in Melbourne. The study looked at the variation in rainfall in Melbourne (400 mm to 1400 mm) and different roof areas (100 m^2 – 200 m^2). The study developed a number of graphs for calculating rainwater tank yield in the Melbourne area for 3 different reliabilities (90%, 95% and 98%). The study considered demand based on the number of occupants in the house. For instance, the study found that for a 3 people household the daily water use was 520 L/day. However, 15 years later the current consumption rate in Melbourne will be 225 L/day (Birrell et al 2005). As a result, the graphs developed by considering the high water usage will not provide the optimum rainwater tank size for the current water consumption which is low. Besides this, the model developed by Duncan and Wight (1991) does not reflect the lowest rainfall series recorded for the last 10 years. Hence, it is important to develop a new set of guidelines that will assist selecting the optimum rainwater tank size considering the current water consumption practices, the most recent rainfall patterns and the geographical location.

Coombes (2002) illustrated the use of the Probabilistic Urban Rainwater and wastewater Reuse Simulator (PURRS) model which used the rainfall input from Disaggregated Rectangular Intensity Pulse (DRIP) event rainfall model. Coombes and Kuczera (2003) analysed the synthetic rainfall generated by DRIP which was fully based on a pluviograph record with a depth of 663 mm. While analysing the performance of a rainwater tank, they estimated the average daily household water use for 12 months in Melbourne. They stated that the rainwater was effectively used to supply domestic hot water, toilet, laundry and outdoor water use. They also calculated water savings for roof sizes such as: 100 m^2, 150 m^2 and 200 m^2. Another important notable aspect of the experiment was that different graphs were drawn for different numbers of people. For this reason by using these graphs, the percentages mains water savings for different occupancy could be obtained. In the above study, the researcher calculated the average retention storage available prior to storm events. The study found that for a 1 kL rainwater tank the storage varied from 0.36 m^3 to 0.61 m^3 and for a 10 kL rainwater tank, the variation was 4.90 m^3 to 8.36 m^3.

Fewkes (2007) reported results using from a behavioural model for simulating the hydraulic performance of rainwater harvesting systems. The study reported the performance of three rainwater tanks installed in different parts of UK to meet the demand for flushing toilets. The study analysed water savings efficiency of the rainwater tanks within a full year. The study found that September and February provided 100% water saving efficiency where as April and July were the lowest water saving months. The study noted that incorporation of rainfall losses into a rainwater tank sizing model was necessary to evaluate the performance.

The South Australian Water Corporation and the Department for Environment, Heritage and Aboriginal Affairs carried out a computer simulation of tank performance to optimize the tank size (DEHA 1999). The study reported a rough estimate of tank size for a 4 person household in Adelaide based on demand (Table 2.1).

Table 2.1 Tank size for different demand type

Demand type	Tank size (kL)
Drinking	0.3
Drinking, cooking and hair washing	1.7
Drinking, cooking and laundry	3.6-4.5

Furthermore, the study developed some graphs to select the tank size based on demand, rainfall and roof size. The study considered 5 random values of demand (60, 100, 200, 400 and 600 L/day) and developed curves for 99%, 90% and 80% reliability for different roof sizes (100 m^2 – 800 m^2). In addition, the study also looked at the variation of mean annual rainfall (150-1200 mm) while plotting these curves.

2.4 Popularity of rainwater tanks

Rainwater harvesting technology is very popular in some developed countries as well as developing countries. The following literature review looks at its popularity and the effectiveness of rainwater as a potential alternative to mains water supply.

Osava (2005) reported that a public-private effort was taken to provide clean drinking water provided rainwater collection tanks to more than 100,000 families in Brazil. The goal was to build 1 million collection tanks by 2008 to ensure water supplies for all poor households in the country's semiarid northeast. According to this study each rainwater tank cost little over 1,500 Reals ($640) to build. The beneficiaries provided the labour, helping to keep costs down. Community solidarity funds were set up with donations from local residents to build more tanks and address other community needs. He also informed that in Brazil's semiarid northeast, the amount of rainfall was at least 200 millimetres a year, enough to provide water supplies to a five- person household for a year if the water that falls on the rooftops was collected and stored. The cylindrical tanks were built with pre-fabricated cement slabs. Each could hold up to 16 kL of water, and they were situated to collect all of the rainwater that drains off the roof. In north-eastern Brazil the rainfall varied between 400 to 800 millimetres a year on average, and at least 200 millimetres during the driest years, making this the semiarid region with the largest amount of precipitation in the world. This means that in a good year, a 16kL tank could be filled by 600 millimetres of rain falling on a 40-square-meter rooftop.

China Daily (2006) reported that every drop of water mattered to Beijing, a city that battled drought for the past seven years. The city's rainwater target was an inspiration that was both commendable and workable, the writer observed. The serious scarcity of water turned out to be a bottleneck in the capital's social and economic development and recent summers were so arid that the local government had to call for voluntary and sometimes mandatory water use restrictions. The study reported that this rainwater harvesting target would provide a total of 230 million cubic metres of water supply for the city. To make this dream into reliability the city built 55 structures, which could store 1.25 million cubic metres of water. The researcher stated that rainwater harvesting on a residential level should be made a mandatory part of building codes to expedite this endeavour.

Besides this, there is a large-scale rainwater scheme in “The Millennium Dome” in London. The roof of the Dome has a surface area of approximately 100,000 m^2. Rainwater is collected using large hoppers, which discharge into a collection ring main that runs around the circumference of the Dome.

Smith et al (2001) stated that increased poor quality ground water combined with quantities of grey water and rain water was identified as potential alternatives to potable water for toilet flushing at the Millennium Dome. An 87m deep borehole was sunk on the Millennium Dome site. The captured rainwater was then discharged into a stormwater culvert containing an 800 m^3 underground sump with three storm discharge pumps, from which rainwater could either be discharged into River Thames, or pumped to the treatment plant. The study revealed the performance of the system which showed that rainwater provided around 10% of the water demand though collection was limited by storage constrains on site; thus, a maximum of 100 m^3 a day of rain could be collected.

At the Nanyang Technological University, Singapore, a study showed that roof runoff from an area of 38,700 m^2 could be collected and used for toilet flushing in the north spine of the University. Computer simulations have shown that a 2542 m^3 rainwater tank would save 12.4% of the monthly cost for water used.

Han (2007) stated regarding a specific rainwater system which was designed for a new construction at the Star City Project in Kwangjin-Gu, Seoul. The study noted that a 3 kL rainwater tank was installed in the basement and divided into three sections of 1 kL each for effective use of rain water. The first section collected rainwater from the unpaved ground surfaces and It was kept empty most of the time except during heavy downpours. The second 1 kL section collected rainwater from the roof and used for toilet flushing and landscaping purposes. The third 1 kL section was filled with fresh water and used for supply during emergencies such as fire fighting or accidents.

Villarreal and Dixon (2005) reported about a computer model which was used to explore the water saving potential of a rainwater collection scheme. This model comprised two modules, the first of which generated time series of domestic appliance usage flows at an hourly time interval using a Monte Carlo technique. The model storage component aggregated the inputs and outputs in hourly time steps assuming a “spill before yield” concept for simultaneous supply and demand, they noted. The term ‘spill before yield’ means that within one time step of the model run, all inputs to the store together with the present volume of water stored are summed and compared with the maximum capacity of the store. Any excess water is ‘spilled’ bypassing the collection system. Then all demands on the store were calculated. Spill before yield leads to slightly conservative results. If there was insufficient water in the store to meet the demand, then the mains potable water supply makes up the difference, they reported. Running the model allowed performance of the system to be analysed. They informed that system performance was described by its water saving efficiency, which was a measure of how much potable water had been saved in comparison to the overall demand, and given by Equation 2.1.

$$\text{Water Saving Effeciency (WSE)} = \frac{(\sum_{t=1}^{T} D_t - \sum_{t=1}^{T} M_t)}{\sum_{t=1}^{T} D_t} \tag{2.1}$$

where,

WSE = Water saving efficiency

D_t = Demand for rainwater (Usage)

M_t = The mains water use when there is an alternative water supply

RD= Total demand for mains water if there is no alternative water source

t = Time period (h)

T = Total time period

Accetturo (2005) stated that Seattle City Hall was an 1860 square-meter building that was completed in 2003, and included a green roof and rainwater harvesting (RWH) system for toilet flushing and on-site irrigation. These systems helped reduce peak flows from the city drainage system and improve water quality by reducing the pressures on the city sewer infrastructure. The RWH collection system can store up to 850 cubic-meter of water in a cistern located in the basement of what was at one time the old municipal building. Collected rainwater is then pumped from the basement cistern to restrooms in the newly constructed City Hall building for use in toilet flushing, as well as irrigation purposes. Stormwater runoff is expected to decrease by up to 75% and reduce indoor potable water use by 30%. These measures result in a significant reduction of stormwater flows and will alleviate loads into the city's combined sewer system. The building has also earned a U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) Silver rating.

The King Street Center is home to the King County Departments of Transportation and Natural Resources in Washington (Accetturo 2005). It is a 30,380 square-meter building that was completed in 1999. Project highlights include a 74 kL rainwater collection system, 80% of all construction waste recycled on-site and 26880 square m^2 of reused/renewed carpet tile. The King Street Center would use approximately 10 ML of potable water a year for toilet flushing. With a 4090 square-meter roof area for collection, it is estimated that about 6.4 ML of domestic water will be saved annually, or 64% of the flushing budget for the year.

The Carkeek Environmental Learning Center is a gathering space for environmental education activities and community meetings in Seattle (Accetturo 2005). The centre had a 16 kL rainwater collection cistern used for toilet flushing and stormwater management, solar electric panels provided by Seattle City Lights Green Power program, 80% recycling or salvaging of demolition and construction waste, and use of regional materials manufactured and salvaged locally. Rain barrels were also installed on-site for irrigation of salmon-friendly native landscaping while being established.

Seattle's Street Edge Alternative Project (SEA Streets) was designed to provide drainage that resembles the natural landscape prior to development and traditional sewer and stormwater system installation. This entailed combining engineering concepts and designs with native soils and vegetation to assist in treating and regulating stormwater flows. The selected residential block for the pilot project had to meet specific criteria such as: a street that does not have existing curbs and sidewalks, located in the watershed area, and not directly served by the existing storm drain system. The pilot project began in 2001, and after two years of monitoring, impervious surfaces were reduced by 11%. Over 1,100 shrubs and 100 deciduous trees were planted, all native vegetation and hardy cultivars, resulting in a 98% reduction in total runoff volume. This successful project is now part of the Seattle Comprehensive Drainage Plan.

Krishna (2007) noted the ever increasing popularity of rainwater harvesting in Texas. Construction of reservoirs, development of well fields and construction of treatment plants are not only time consuming but also costly. As a result, Texas residents built cisterns and collected rainwater from their rooftops to serve their daily needs. The study stated that over 9,000 rain barrels were sold in the past few years by the City of Austin at a discounted price of $60 each to residents. In addition to discounted rain barrels, the study noted that the city of Austin also provided rebates for larger rainwater harvesting systems to encourage rainwater harvesting. It is estimated that a total of about 15,000 rainwater harvesting systems were operating in Texas with a view to meeting both potable and non-potable water needs.

Salas (2007) stated regrading the success of rainwater harvesting in Kusa Village, Kenya, with an annual rainfall of 900 mm. The study noted that at the time of project evaluation, there was one tank for every three homesteads or a penetration level of one tank for every 20 people. Over 800 5m^3 of rainwater tanks were constructed which supplied 20% of the water needs in the area, the study observed.

Lo et al (2007) reported about rainwater utilization in lighthouses for domestic and washing purposes in Taiwan. The study noted that lighthouse buildings, residential buildings and additional ground catchment surfaces were constantly and effectively used to collect rainwater. These lighthouses used both roof top and ground surface as catchment areas, the study observed. Roof top rainwater was collected through gutters, down pipes and drain pipes and delivered to underground storage tanks, the study noted. The study found that simple filtration treatment was used to provide water for cleaning lighthouse and building walls, plant irrigation, and toilet flushing. A small amount is boiled and used for domestic drinking purposes.

In Berlin, at Daimler Chrysler Potzdamer Platz, roof runoff from 19 buildings (total area 32,000 m^2) is collected and stored in a 3500 m^3 rainwater basement tank (RHA 2007). The water is then used for flushing toilets, watering gardens and roofs with vegetative cover, and for the replenishment of a vegetated pond. Another example in Berlin is the Belss-Luedecke-Strasse building estate (RHA 2007). Rainwater from roofs (7000 m^2) is stored in a 160 m^3 tank along with rain runoff from streets, parking places and pathways (4200 m^2). After treatment, the water is used for toilet flushing as well as for garden watering. About 58% of the rainwater is retained locally by using this system. A 10-year period simulation showed that a 2430 m^3 potable water savings per year could be achieved.

In Sweden, 20% of household water use was for flushing toilets, 15% for laundry, and 10% for car washing and cleaning (Villarreal and Dixon 2005). The study noted that collected rainwater could supply their uses with many economical and environmental benefits. By capturing and storing significant quantities of stormwater for landscape maintenance and improvement in residential areas, peak demands could be reduced, water conserved, and many stormwater management problems mitigated, they monitored. The study illustrated about the popularity of rain water harvesting for domestic use in different parts of world. The study showed the examples in Japan where several large scale rainwater collection systems were introduced. They observed that in three multipurpose stadiums located in Tokyo, Nagoya, and Fukoka with capacity for a large number of spectators, rainwater was used for WC flushing and irrigation of plants. The catchment areas were 16,000, 25,900 and 35,000 m^2, respectively with the tank volumes were 1000, 1800 and 1500 m^3, respectively. A 19-month follow-up study carried out at the Fukoka Dome showed that rainwater provided 65% of the volume of low quality water. Approximately 75% of the total rainfall on the roof was used, representing a significant economic saving, they reported. Moreover, also in Japan, at Sumida City Office, rainwater was collected from a 5000 m^2 roof and stored in a 1000 m^3 tank located in the basement of the building. The total amount of rainwater used for toilet flushing was 4658 m^3 in 1998, which represented 36% of potable water used for flushing toilets.

Wessels (1994) reported regarding grants and subsidies available in different German cities and towns to encourage householders to construct rainwater tanks. A grant of \$600-\$1200 per household was available along with a further subsidy of \$3 per m^2 of roof area draining to any tank linked to a seepage well in Osnabruck, On the basis of this subsidy, savings in water charges (\$0.56/m^3) and an annual rainwater drainage fees waiver of \$1.30 per m^2, the pay back period for investment in a tank seepage well system constructed at a new house was estimated to be 12 years Wessels reported. He also stated that without the subsidy and constructing a system at an existing house, the investment would be recouped only in 19 years. Costs and the return period on investments would be greatly reduced if householders were prepared to undertake some of the work themselves, he observed.

According to the water trade association British Water, rainwater harvesting should be compulsory for all new buildings within the next three years (Utility Week 2006). The study reported that the body launched a campaign “Save the Rain” sponsored by engineering group Hydro International, to persuade British households for saving rain water .The campaign would lobby for new regulation and for grants to encourage householders to adopt water-saving devices, the study illustrated. Thirty per cent of treated water from the main water supply was used to flush toilets and a properly installed rainwater collection system could save this, the study noted.

2.5 Review of use of alternative water source

It is a common understanding that people will show their preference to install rainwater tank primarily to harvest stormwater from their roof and conserve their mains water use. Garden watering, laundry use and toilet flushing consume most of the domestic water use. A typical home uses approximately 225 kL of water each year (Birrell et al 2005). Duncan and Wight (1991) noted that due to variation of number of people in a household the demand for water could vary considerably. Table 2.2 delineates the average daily water use in Melbourne for different number of people in a house (Duncan and Wight 1991). Figure 2.3 shows the percentage of different types of domestic water use in Melbourne.

Table 2.2 Relationship between number of people in a household and daily water use

Number of people in a household	Average Daily water use (L/day)
1	220
2	370
3	520
4	640
5	750
6	850

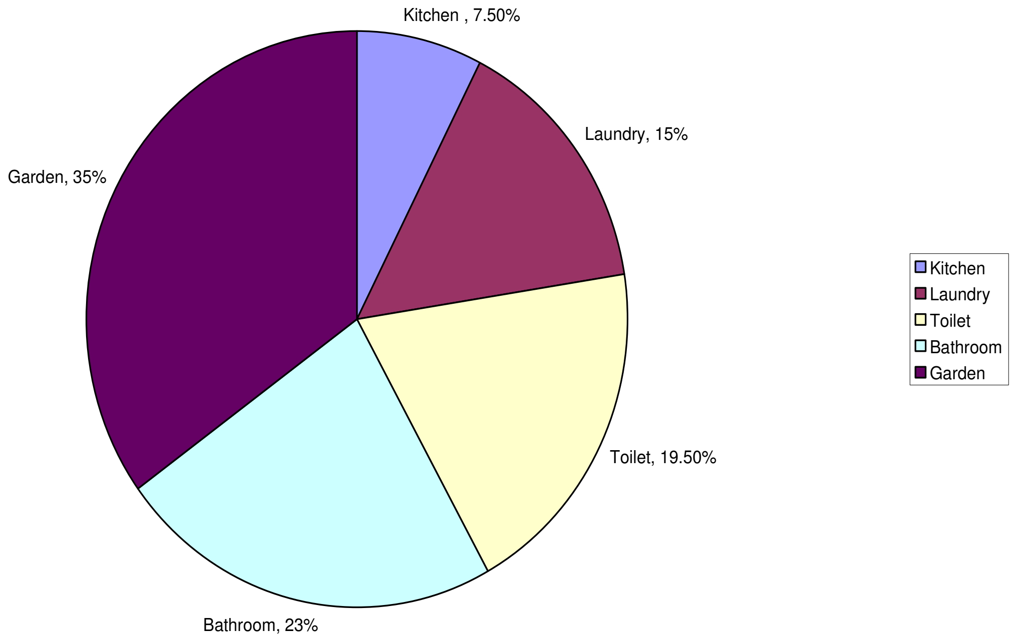

Figure 2.3 Different types of water use (outdoor and indoor) (Melbourne Water 2006)

Some people argue that rainwater tank use should be restricted for garden watering only. However, the weakness of this argument is that if a potential rainwater tank user stick with using rainwater only for garden watering it will soon be found that the tank will remain full and unused during the winter months when the garden does not require watering.

The Victorian State Government introduced the “Water Smart Gardens and Homes Rebate Scheme” which allows every household a chance to conserve his water resources and save money (Department of Sustainability and Environment, 2007). The Government has committed $10 million over four years to provide a means and an incentive for Victorians to connect a rainwater tank to substitute reticulated water supply to conserve future water resources. The Government has recognised the importance of plumbing the tank to the toilet and offered a cash rebate only for the installation of connected rainwater tanks (Department of Sustainability and Environment, 2007).

According to the “Building Commission Victoria” all new houses in Victoria must include water saving features according to 5 Star standard introduced by Victorian Government (Building Commission Victoria, 2007) Victoria's 5 Star Standard for new homes is a key characteristic of the Victorian Government's environmental policy and will help save water resources. From 1 July 2005 compliance required installation of a 5 Star energy rating for building fabric plus water conservation measures and a 2 kL rainwater tank or a solar hot water system in all new houses and apartments. According to the Government, as a result of the 5 star ratings, Victorians will enjoy new homes that are:

- Good quality and more comfortable
- More reasonably priced
- Environmentally effective and sustainable; and
- Beneficial for Victoria's economy.

Sustainable Housing (2007) reported that in Western Australia a range of measures, collectively named Five Star Plus, to make houses more energy and water efficient was announced by the Premier Hon. Alan Carpenter. The second stage of the Five Star Plus standards involved installation of plumbing to toilets to allow for alternative water supply and the use of an alternative water supply i.e. rainwater tanks for toilet flushing and laundry use.

Rainwater tanks are now being used extensively in all large scale residential projects in Melbourne. For example, Aurora one of the most innovative housing developments in Melbourne has the ‘rainwater for hot water’ system (VicUrban, 2007). Rainwater harvested from household roofs is collected in a rainwater tank. From the rainwater tank, water is pumped through solar panels on the roof. This water then feeds into the gas hot water system and then into the kitchen, laundry and bathrooms. Aurora householders can use up to 30% less reticulated water supply by using the rainwater tank for the hot water system.

Department of the Environment and Heritage (2006) reported that Investa Property Group (IPG) constructed a Foster & Partners designed environmentally sustainable building in Sydney in 2005. A rainwater collection system was installed to collect most rainwater discharged from the building. Water from the 75 kL tank is used for garden watering, and for toilet flushing on the ground floor.

The Cairnlea EcoHome in North West Melbourne sets new standards in environmental sustainability, featuring rainwater tanks, grey-water systems, energy smart design and building materials, solar hot water and indigenous landscaping (Rahman et al 2005). The study reported that rainwater was harvested and stored in a 5 kL tank for garden watering.

Green Square South Tower in Queensland has introduced radical environment friendly applications for sustainable commercial construction within Queensland (Your Building 2007). The entire roof of the Green Square South Tower is used to collect rainwater from a 90 kL underground storage tank which is used to supply non-potable water for toilet flushing and landscape irrigation. The design of the non-potable water system is such that there is no potable water makeup used in the storage system to allow the tank to run dry and provide the maximum possible storage capacity when it does rain. About 1.7 ML per year can be saved due to use of this large rainwater tank.

2.6 Summary and conclusions

It is a matter of great concern that less than 2% of main water supply is used for potable purposes although 100% of the mains water is of potable water quality (ABS 2001). However, a majority of the residential water consumption is due to outdoor use, hot water as well as toilet flushing (Coombes et al, 2002). Many households have shown their willingness for using rainwater as an alternative and renewable source of water even in areas that receive mains water. Water restrictions which were implemented from 1 September 2006 in Melbourne would help maintain supply until further augmentations are built securing Melbourne's water supply for the next 50 years and beyond (Our Water Our Future, 2006). The research work carried out outside Australia shows that by using rainwater tanks it is possible to save considerable amount of reticulated water supply (Accetturo 2005; RHA 2007; Salas 2007).

In Victoria the use of domestic rainwater tanks is an established and relatively common practice, particularly in rural and remote areas. Between 1994 and 2001, 13% of people in Victorian households used rainwater tanks, with 11% of them using rainwater as their prime drinking source (ABS 2001). As reported earlier, the guidelines provided by Duncan and Wight (1991) for sizing the rainwater tanks in Melbourne are inadequate considering the fact that those guidelines were based on rainfall data before 1991 when the phenomenon of climate change and persistent water restriction were inconceivable. In addition, the most recent guidelines provided by WSUD (2005) were developed considering only toilet flushing to be the demand for rainwater. Nor do these guidelines consider the wide rainfall reliability across the Greater Melbourne area. Hence, these guidelines have to be superseded due to the current rebate scheme from September 2007 which provided maximum rebate for using rainwater not only for toilet use but also for laundry use and more.

Rainfall varies considerably in Melbourne when one moves from west to north east. For this reason, one size fits all philosophy is inappropriate due to spatial variation of rainfall across Melbourne. As a result, it is important to develop guidelines which reflect all the present circumstances when optimising the tank size. Hence, the primary objective of this study is to develop a tool to calculate the optimal rainwater tank size based on the demand, roof size, available area, supply reliability and rainfall characteristics of the geographic location of the dwelling. The development of this tool and the methodology behind development of this tool are detailed in Chapters 3 and 4.

Rainwater can save huge proportion of mains water supply if used effectively and widely for indoor as well as outdoor use. Due to persistent drought (12^{th} consecutive years) in Melbourne there is a legitimate concern regarding efficacy of future supply reliability even with widespread use of rainwater tanks. Besides this, the recent decision of Victorian government to construct a desalination plant to deal with future water shortage has created doubt among the people regarding the on going commitment of the Government to rainwater harvesting. However, the desalination plant is not expected to be operational until end 2012. In addition, wide use of rainwater tanks will assist with minimizing desalinated water use estimated to cost as high as \$3.50/kL and delay the need of further water harvesting infrastructure in the future. As a result, it is important to analyse the performance of rainwater tanks in this drought periods and its reliability to deliver supply preferably in the next five years to minimize the use of reticulated water supply. All the above stated issues have been considered and discussed in detailed in Chapter 5.

The efficacy of any sustainable water technology is determined not only by the amount of water that can be saved by using the technology but also how effective it is from a water quality point of view. Australia is currently confronted with a severe water supply and water quality problems. Furthermore, it is expected that due to drought, pollution, over-extraction and climate change the situation can be exacerbated in the coming decades. Rainwater is free from pathogens and faecal contamination if tanks are well protected with covers and the first-flush is avoided. In addition, the primary sources of faecal contamination of the rainwater runoff can originate from faecal matter deposited by birds, frogs, dead animals and insects either on the roofs or in the water tank itself. However, in case of rainwater tank the issue of water quality is not that significant considering the fact that the water will exclusively be used for non potable purposes. On the other hand by using some water quality improvement devices (first flush device) the water quality can be further improved. This has been discussed in detail Chapter 6.

One of the important considerations of selecting a rainwater tank size for a potential customer is the total expenditure requirement. However, the recent rebate scheme introduced by the Victorian government to popularize rainwater harvesting across Melbourne will encourage Melbournians to install rainwater tank for domestic water conservation. As a result, community education is imperative to make people more knowledgeable about the significance of rainwater harvesting. Cost-effectiveness analysis has been carried out in Chapter 7 to compare the cost of water in reticulated water supply and rainwater in the long run.

Chapter 3
Variation In Tank Sizes With The Geographic Location And The Demand

3.1 Introduction

Melbourne is in the midst of twelfth consecutive years of drought with the 2008 cumulative rainfall continuing to be significantly below average. It is expected that if the drought becomes more severe Melbournians may have to face Stage 4 water restrictions which totally bans external water use (garden watering). In Melbourne, legislation has been amended to make it possible to use rainwater for garden watering, toilet flushing, laundry use and in hot water systems (i.e. for non potable purposes). In addition, continuing urban development is augmenting the area of paved and roofed surfaces, producing greater stormwater runoff. Water Sensitive Urban Design (2005) considers rainwater tanks as an internal element for stormwater harvesting because it can reduce the amount of runoff discharged to receiving waters, the demand on the reticulated water supply system and the cost of water treatment infrastructure to improve stormwater quality before discharging to waterways.

As mentioned in chapter 2, there is a significant variation in rainfall across Greater Melbourne. The use of rainwater tanks to meet some of the domestic water demand is becoming popular in Greater Melbourne and nearby suburbs. One of the most important features in rainwater harvesting is the selection of the appropriate tank size depending on the local rainfall, roof area, and expected demand for rainwater. In this chapter a relationship between tank sizes and above parameters will be developed.

Based on the research reported in Chapter 2 a simple water balance method is adopted to obtain the optimum tank sizes from different roof sizes to meet different demand levels. The variation of tank sizes determined across Melbourne will be reported in this chapter.

The WSUD model recommended a procedure to calculate the tank sizes for Victoria. The preceding chapter reported weaknesses with the applicability of the above model. As a result, a simple water balance model will be initially used in this study to optimize the size of the rainwater tanks.

3.2 Overview of study areas

The data base for the study consists of 20 stations distributed across the Greater Melbourne metropolitan area in km^2 (Figures 3.1). The variation of mean annual rainfall (MAR) shown in Figure 3.2. The daily rainfall data obtained from Melbourne Water were used for the analysis. Table 3-1 shows the rain gauge locations; number of years of data used and the mean annual rainfall of the 20 stations used in this study. From the figures and the values in the table, the mean annual rainfall of the study area varied from 454 mm in the west to 1054 mm in the north east of Melbourne. From Figures 3.1 and 3.2 it can be observed that there is significant variation in rainfall when one travels from east to west of Melbourne.

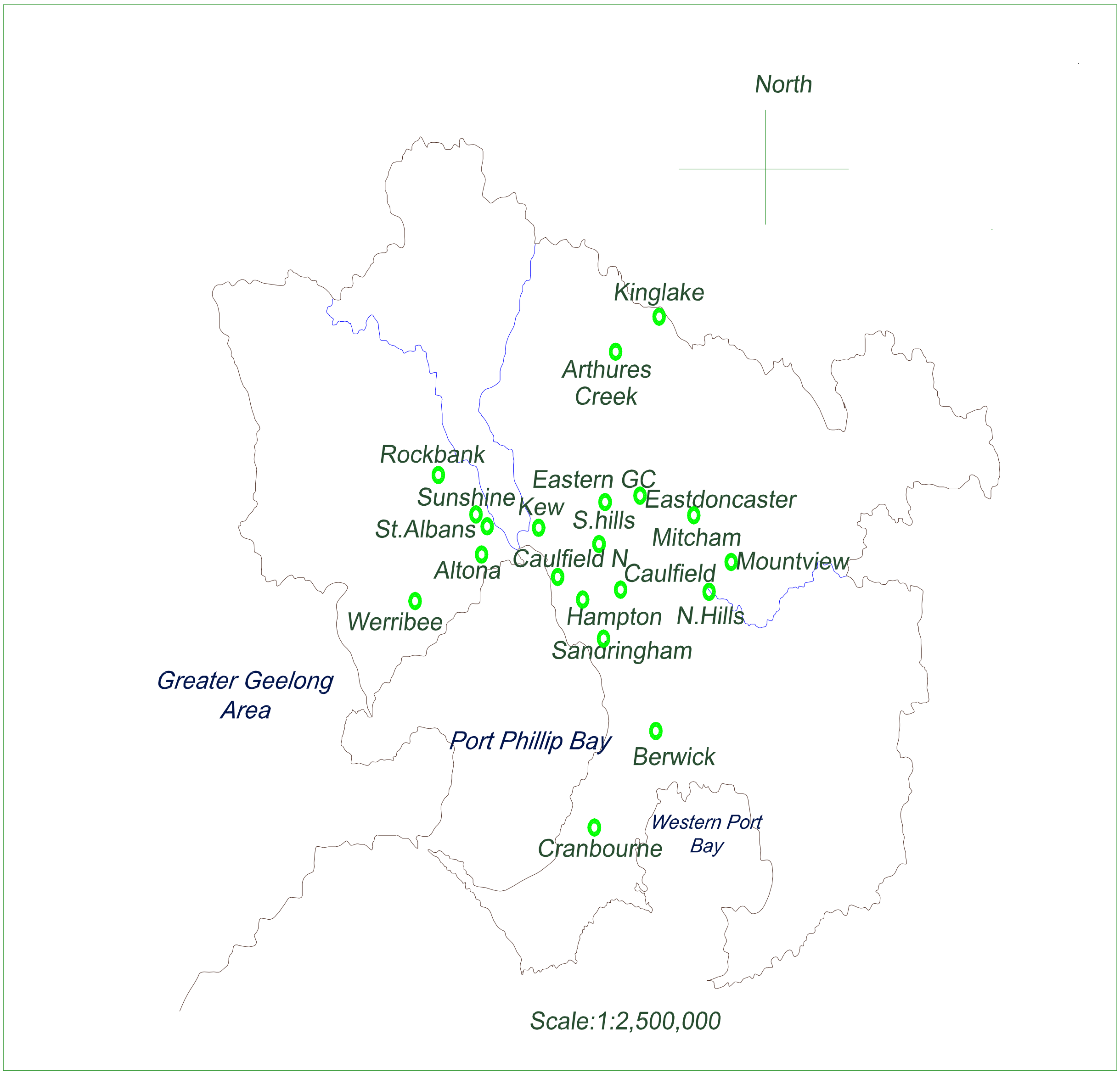

Figure 3.1: Locations of the rainfall stations used in this study

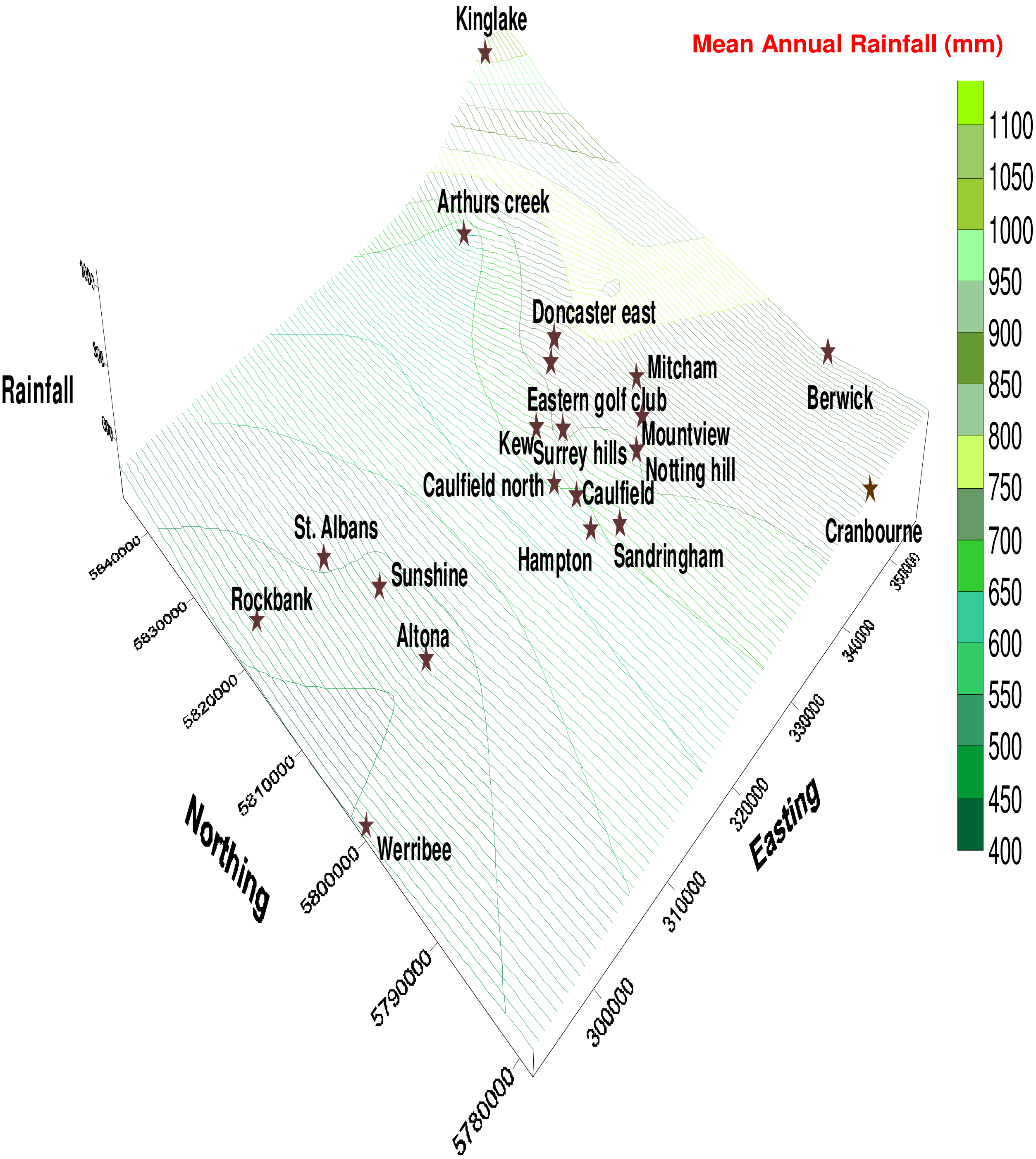

Figure 3.2 Variation in mean annual rainfall (mm) in Greater Melbourne (3D)

Table 3-1: Details of the rain gauging stations and no of years of data used for the study

Rainfall Station	Station ID	Easting	Northing	No of years of data	MAR (mm)
Altona	587047	305612	5806234	15	454
Arthurs Creek	229620	341612	5839084	20	620
Berwick	586199	356012	5791784	20	710
Caulfield	586115	326562	5803234	19	650
Caulfield North	586194	326172	5806634	7	710
Cranbourne	586375	348112	5778484	20	746
Doncaster East	586037	338062	5817334	15	736
Eastern Golf club	586010	333632	5816484	15	733
Hampton	586036	325532	5799254	15	666
Kew	586175	329092	5813404	15	690
Kinglake	586205	351412	5845734	7	1054
Mitcham	586006	340722	5812424	20	810
Mountview	586197	339392	5804764	7	700
Notting Hills	586023	335412	5803384	16	730
Rockbank	231105	293512	5824884	20	454
Sandringham	586184	327412	5796584	15	700
St. Albans	587051	304912	5821934	17	525
Sunshine	587004	308052	5817734	20	495
Surrey Hills	586176	333442	5811744	15	725
Werribee	587030	292732	5800764	15	453

(MAR – Mean Annual Rainfall)

3.3 Rainfall data

The number of years of available data varied from minimum of 7 years to maximum 20 years among the rainfall stations. A quality code (Melbourne Water) was given for each daily data set. The quality code varied from 1 – 255. Table 3-2 delineates the major quality codes that were associated with the rainfall data. A number of rainfall data were either missing or given as an accumulated value. The missing data were infilled before the analysis. Most of the rainfall data have the quality code of 1, 2 and 255. However, there are few rainfall data which had codes of 50, 140 and 151. As a result, the impact of these rainfall data on the analysis was ignored by retaining them as they were.

Table 3-2 Quality code for rainfall data used in the analysis (Melbourne Water)

Code	Description
1	Very Good data - no editing required (or 1-5mm error)
2	Good quality edited data
50	Good or Reliable data (5-10mm error)
140	Estimated accumulated data
151	Poor Data (15-25mm error)
255	Invalid or lost data

3.3.1 Filling in missing data

The missing data (Code 255) were infilled before carrying out the analysis. There are number of methodologies to fill the missing daily rainfall data. For example,

- Arithmetic average method
- Normal ratio method
- Regression method (Simple and multiple)

For filling missing data of a particular station the daily rainfall data of a nearby station was considered. For example, for filling the missing data for Caulfield, the daily rainfall data from the nearby rain gauge (Hampton) was considered. In this study simple linear regression analysis was used to fill the missing data. Figure 3.3 depicts the linear regression equation that was used to fill the rainfall data for the Caulfield rain gauge. The prime characteristic of the simple linear regression model is that it is a hypothesized relationship between Y (Caulfield rainfall) and X (Hampton rainfall) where Caulfield rainfall value is the dependent value and Hampton rainfall value is the independent value.

For obtaining the linear regression equation, the pair (Hampton rainfall, Caulfield rainfall) was regressed on a daily basis for a period of 15 years. As a result, a scatter plot of n points in two dimensions (X & Y) represents the points graphically. A linear regression equation ($Y = 0.91X+0.11$) was obtained and used to infill the missing data of Caulfield rain gauge.

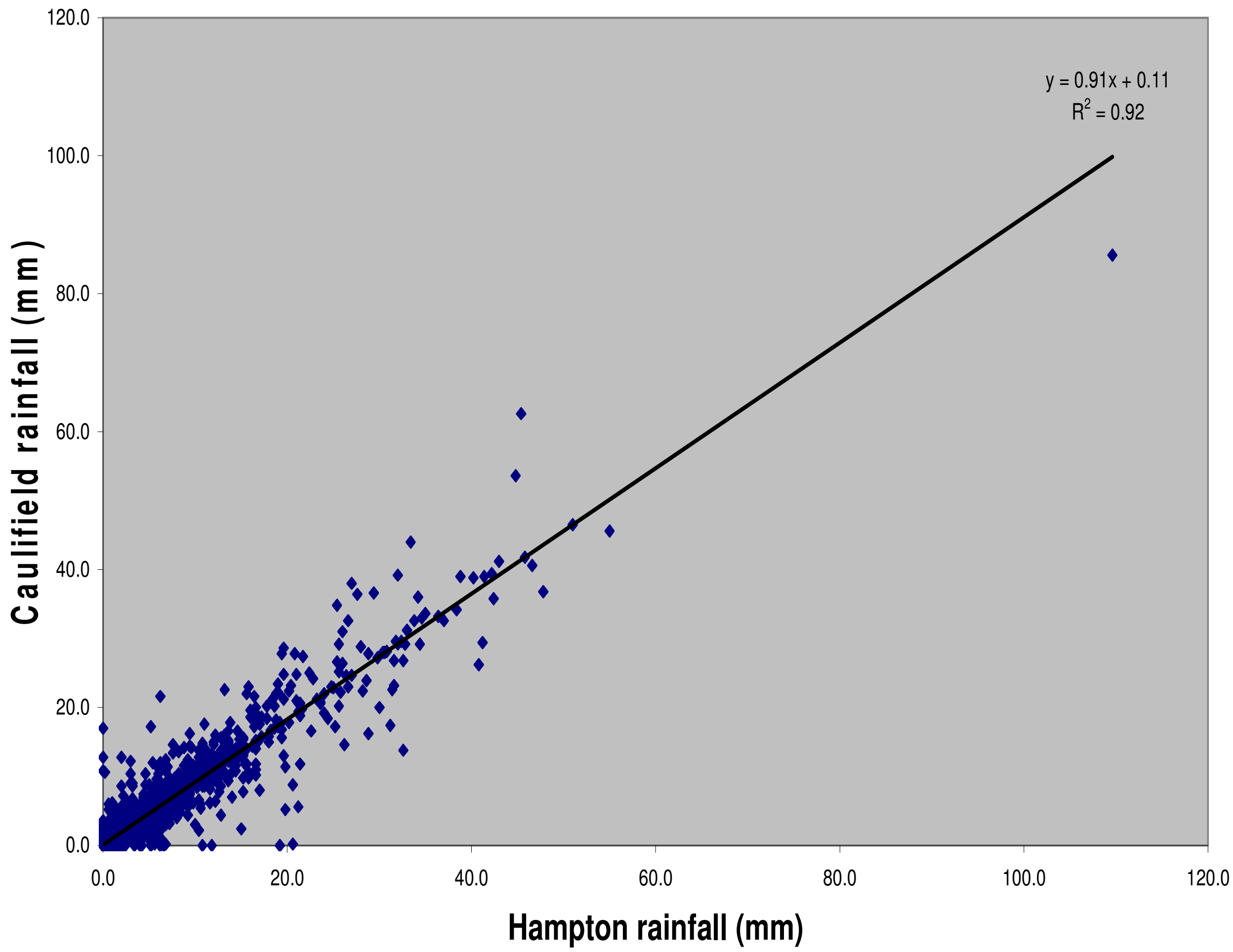

Figure 3-3: Regression relationship between daily rainfall data at the Caulfield and Hampton rain gauges

3.4 Data analysis

A statistical analysis of rainfall data at each station was carried out to determine the variation of rainfall between stations. Statistical analysis is an integral part of any research based on rainfall data. Different statistical methods can be used to understand the characteristics of collected data. The following analyses were undertaken on the daily rainfall data for all the 20 different stations used for the study:

- Maximum, minimum, average annual, standard deviation and skewness of rainfall data for each station.
- On average total rainy days in a year, rainy days in summer and rainy days in an individual month for all the stations.

All these statistical analysis will provide a better understanding of the rainfall pattern, variation in rainfall through out the year and unusual incidents (floods or droughts) in different parts of Melbourne. Figure 3.4 depicts the variation of rainfall of the stations used in the study.

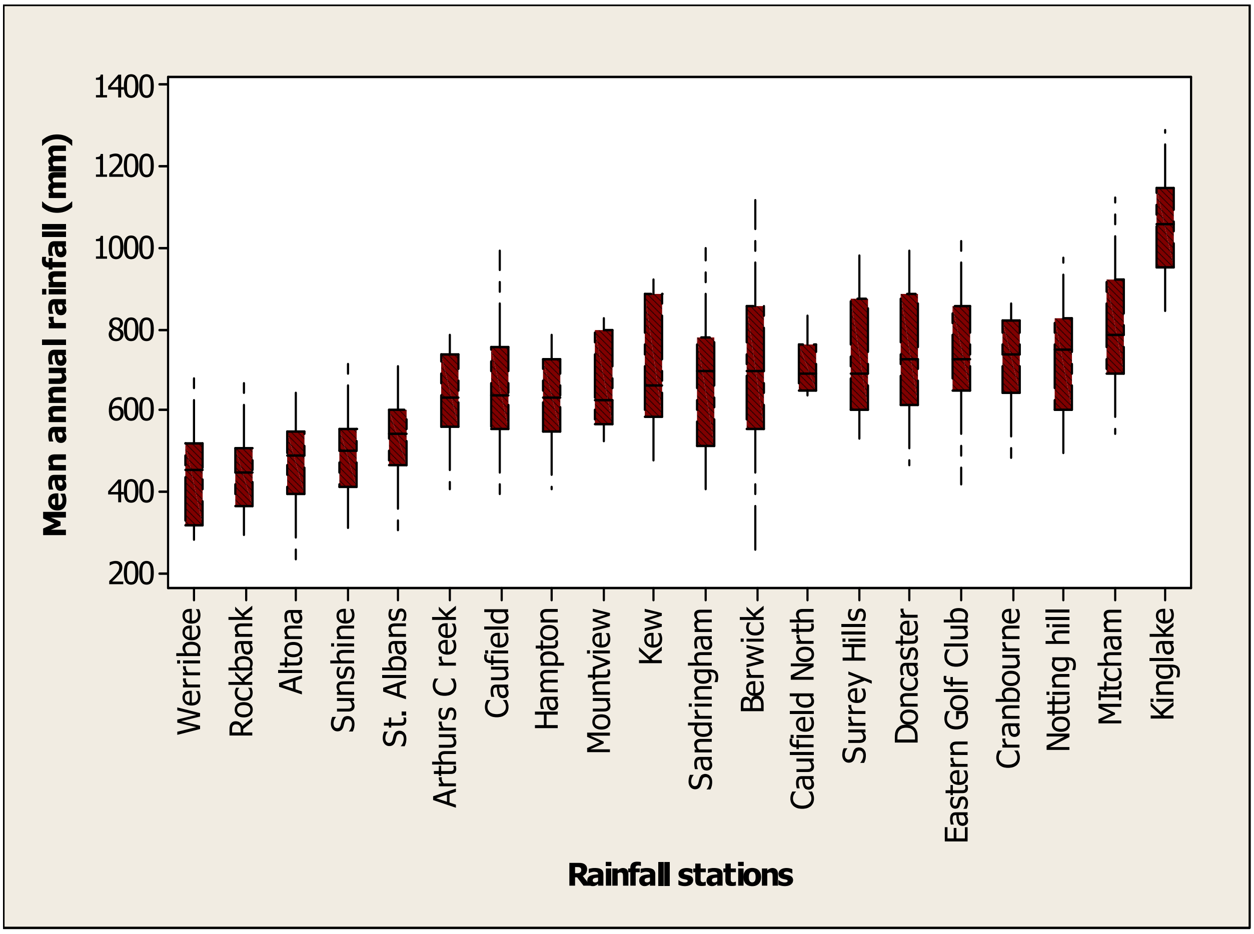

Figure 3.4 Variation in annual rainfall values for 20 rainfall stations used in the study

Table 3.3 depicts the basic statistics of the data used at each station. Mean daily rainfall was calculated by taking the average of daily rainfall data for the 20 stations. Standard deviation indicates the spread of rainfall data and an indicator of the variability of rainfall data over time. The standard deviation of rainfall data for different stations helps to compare the rainfall pattern. Skewness is a measure of the degree of asymmetry of the distribution of data. Co-efficient of variation is the statistical measure of the dispersion of data points in a data series around the mean. The number of rainy days in the analysis is a measure of intensity of rainfall in a day. In this study, a day with rainfall >= 3 mm is considered as a rainy day. The variation in rainfall within Greater Melbourne is evident from the statistical data in Table 3.3. The table shows that station with more annual rainfall has more rainy days in comparison with the stations with low mean annual rainfall. In addition, the standard deviation is high at the stations with high mean annual rainfall values.

Table 3.3 Statistical parameters for 20 rainfall stations used in the study

Rainfall Stations	MDR* (mm)	Standard deviation (mm)	Coefficient of variation	Skewness	MAR** (mm)	Average rainy days (yearly)
Werribee	1.1	3.9	3.5	7.8	453	36
Altona	1.1	4.4	4	7.9	454	38
Rockbank	1.1	4.1	3.7	10.6	454	37
Sunshine	1.2	2.7	2.3	8.4	495	41
St. Albans	1.3	4.6	3.1	9.8	525	45
Arthurs Creek	1.6	4.8	3	6.7	620	53
Caulfield	1.6	4.8	3.0	5.5	650	51
Hampton	1.7	5.0	2.9	5.9	666	53
Kew	1.7	5.0	2.9	6.7	690	60
Mountview	1.8	5.4	3.0	8.5	700	60
Sandringham	1.8	5.1	2.8	5.2	700	58
Berwick	1.8	5.0	2.8	5.3	710	58
Caulfield North	1.7	5.5	3.2	6.9	710	55
Surrey Hills	1.8	5.0	2.8	4.8	725	64
Notting Hills	1.9	5.4	2.8	6.8	730	61
Eastern Golf club	1.8	5.4	3.0	7.0	733	34
Doncaster east	1.9	5.2	2.7	5.9	736	62
Cranbourne	2.0	4.9	2.5	5.2	746	64
Mitcham	2.1	5.4	2.6	4.6	810	70
Kinglake	2.7	7.0	2.6	8.0	1054	86

* - MDR – Mean Daily rainfall

** -MAR – Mean annual Rainfall

3.4.1 Statistical techniques for data analysis between observed and simulated data

Hydrologists often use a variety of statistical techniques to compare the relationships between observed and simulated values. In addition to mean and standard deviation of a data set, Coefficient of Determination (R^2) and Coefficient of Efficiency (E) are also important parameters to measure the goodness of fit between observed and simulated values. Satisfactory goodness of fit parameters increases the confidence of the simulated value. Descriptions of those parameters are given below.

Co-efficient of Determination (R^2): It is a measure of the degree of association between the observed and simulated values. It certainly indicates the deviation of the estimated values from the line of best fit or the regression line. Aitken (1973) reported the equation of R^2 as given by Equation 3.1.

$$R^2 = \frac{\sum (q_c - \overline{q_c})^2 - \sum (q_c - q_{est})^2}{\sum (q_c - \overline{q_c})^2} \qquad (3.1)$$

where,

q_c = observed discharge

q_{est} = estimated discharge obtained from the regression line of q_c on q_e

q_e = estimated discharge.

Coefficient of Efficiency (E): It describes the degree of association between observed and estimated flows. It indicates the deviation of estimated values from the observed values. Aitken (1973) reported the equation of E as given by Equation 3.2.

$$E = \frac{\sum (q_c - \overline{q_c})^2 - \sum (q_c - q_e)^2}{\sum (q_c - \overline{q_c})^2} \qquad (3.2)$$

3.5 Estimation of rainwater tank size

3.5.1 Development of rainwater tank model

A simple daily water balance model is developed to calculate the rainwater tank size (Equation 3.3). The volume of rainwater in the tank depends on the volume of water flowing into the tank and the demand for rainwater as an alternative water source to conventional supply. It is important to ensure that there is enough water in the tank to supply the demand with minimum risk of the tank being empty (maximum reliability). The daily storage level of the water tank would depend on the frequency and the amount of precipitated rainfall and the end use. A daily time period was considered for the study as it is important to ensure that there is sufficient water for the domestic use intended. Evaporation of water from the tank was not considered assuming that the tank would be closed. The water balance equation used for the study is given in Equation 3.3.

$$S_{t+1} = S_t + Q_t - D_t \qquad 0 \le S_{t+1} \le C \tag{3.3}$$

where,

S_{t+1} = Storage volume in the tank at the end of t th day

S_t = Storage volume at the beginning of t th day

Q_t = Runoff volume from the roof into the tank on the t th day

D_t = Total demand for water on the t th day

C = Active tank capacity

As first step, the tank capacity C was assumed. The daily runoff from the roof (Q_t) depends on the daily precipitation. The daily water demand (D_t) will depend on number of factors. It is a recommendation in Melbourne, Australia to use the rainwater only for toilet flushing, laundry use, hot water systems and for garden watering. As a result, the water demand will depend on number of factors such as the number of occupants in the house, the garden size and the weather. Equation 3.3 was applied at the end of each time step (daily) to obtain the water storage level. On a particular day if the water storage level (S_{t+1}) was greater than the tank capacity (C) the excess water will spill over and the tank storage level and at the end of the day will be equal to C. The amount of water spilled is calculated using Equation 3.4. The probability of tank having sufficient water to meet the demand was given as reliability (Equation 3.5). If the required reliability was not achieved with the assumed tank capacity, a new tank size (C) was assumed and the above procedure repeated until the required reliability level was achieved. Usage of water can be calculated from Equation 3.6.

$$\text{Spill on the t}^{th}\text{ day} = S_{t+1} - C \tag{3.4}$$

$$\mathrm{Re} = \frac{P}{N} \times 100 \tag{3.5}$$

$$\text{Usage} = \text{Demand} \times P \tag{3.6}$$

where,

Re = Probability of the tank being not empty as a percentage (reliability)

P = Number of days the tank does not meet the full demand (not empty) $S_{t+1} > 0$

N = Total number of days.

3.5.2 Determination of roof runoff (Q)

The volume of water that could be collected is important to optimise the size of the rainwater tank for sustainable water use. Equation (3.7) was used to calculate the roof runoff volume.

$$Q = I_{eff} * C_R * A \qquad (3.7)$$

where,

Q = Daily runoff (L)

I_{eff} = Daily effective rainfall (mm) calculated as given in Equation 3.8

C_R = Co-efficient of runoff

A = Roof area connected to the tank (m^2)

The stormwater quality of the initial discharge from the roof surface or from the impervious surface after an event is of poor quality due to accumulation of dust, sediments, bird and animal droppings, and leaves and debris from the surrounding areas. It is necessary to separate a fixed portion of rainfall which is called the first flush when calculating the discharge into the rainwater tank. Yaziz et al (1989) and Jenkins and Pearson (1978) noted that the first flush contained large amounts of dust, animal droppings and debris. Coombes (2002) verified this observation while monitoring the roof water in Figtree place. However, there are differences of opinion regarding the amount of first flush to be kept out of reuse to ensure maximum water quality. Yaziz et al (1989) reported that subtracting the first 0.33 mm of rainfall from the total daily rainfall as the first flush would significantly improve the roof water quality. Abbott et al (2006) reported that the use of first flush device would dramatically improve the water quality of rainwater. The study noted that samples taken from the tank fitted with the first flush device consistently yielded low or zero total coliforms and E coli throughout the study. The above author also observed that the water samples taken from the first flush device contained high levels of total coliforms. However, Jenkins and Pearson (1978) stated that separating the first 0.25 mm could ensure good quality of water. Coombes (2002) developed the FFpit model to simulate the performance of the first flush. The study analysed the performance by considering 1 mm of first flush. In addition, the study recommended the optimum first flush device dimensions for different roof areas. For instance the study observed for a roof area of 100 m^2 the pit area should be 0.26 m^2 and 0.4 m^2 for a 100 m^2 and 250 m^2 roof areas respectively. In the current study, first flush was taken as 0.33 mm even though the rainwater will be used for non potable domestic use. The daily effective rainfall was calculated as given in Equation 3.8 after subtracting the first flush from daily rainfall.

$$\text{Daily effective rainfall, } (I_{eff}) = \text{Daily rainfall - First flush} \quad (3.8)$$

A runoff coefficient value of 0.8 was used in the study to account for loss of water due to evaporation and minor infiltration from the roof surface (Lancaster 2006, DEHA 1999). Furthermore in some instances there will be overflow from roof gutters.

3.5.3 Determination of demand for water (D_t)

As mentioned earlier, according to the Victorian Government regulations the rain water can be used for toilet flushing, garden watering and laundry use and in hot water systems. Only the first three demand types were considered in the study and the water used in the hot water system was not considered because anecdotal evidence from water authorities suggest that the percentage of users connected to the hot water system is minimal. However, this may change in the future and if necessary, the methodology presented here in sufficiently robust to incorporate this. Toilet flushing and laundry use were considered as indoor use whereas garden watering is an outdoor use. The indoor demand depends on the number of occupants in a house. However, garden watering depends on the season summer or winter and the garden size. In this study, the demand for garden watering was constrained to be occurring only in the summer season. Total indoor demand was calculated by using Equation 3.9.

$$\text{Total indoor demand, } (D) = \text{Demand (L/p/day)} \times \text{No. of persons} \quad (3.9)$$

Water Efficiency Labelling and Standards (WELS, 2004) reported that by using water efficient toilets it was possible to save up to 22% of water. The study revealed that an old style single flush toilet could use up to 12L of water in one flush while water efficient duel flush toilet could use less than 4L. The above study encouraged to replace traditional single flush toilets with water efficient dual flush toilets because it could save up to 51Lpcd. In addition, Museum Victoria (2004) elaborated that a leaking toilet could waste up to 16000 litres of water per year. According to the above report the modern dual flush toilet would use 3L to 6L of water per flush which is 30% less than older dual flush and 67% less than that of single flush toilet.

According to (WSAA Facts 2000), during the first 12 months of monitoring in 2000, the healthy home project consumed 241kL of water (661L/day). The study also revealed that equivalent mains water consumption by households in other large urban cities in Australia. Brisbane, Sydney and Melbourne consumed 242kL/yr (320,000 households); 245kL/yr (1,440,000 households) and 240kL/yr (1,250,000 households) respectively during year 2000. Gardner et al (2000) expressed that approximately 30% of the 66L/day is used for outside purposes (mainly garden watering) According to the above study the highest internal use percentage is for bathrooms (30%) followed closely by toilet flushing (18%).

Gato et al (2004) presented the results from the 2002 study. They reported that average water consumption for toilet flushing was 16L/person/day. They also noted that out of 24 households 63% of the toilets were dual flush toilets whereas 37% were single flush toilets. They also observed that the volumes of toilet cisterns ranged from 6L to 9L for single flush and 6/3L to 9/4.5L for dual flush. Roberts (2004) stated that a house with a traditional garden had average annual total water usage of about 247kL/year (677 l/day). He also noted that a house with no garden had total water usage of about 146kL/year (402L/day). Besides this, for all garden types the average annual water use was set at 244kL/year (668L/day). For all garden types the water demand in summer was 69kL/year (190L/ day).

Gato (2006) reported results analysing end use data during three monitoring periods in summer 2000 and in the summer and winter period in 2004 from 24, 99 and 80 households respectively. The study also reported that garden watering was dependent on the following parameters.

- Method of watering
- Duration of watering
- Frequency of watering in a week

Gato (2006) reported that the average duration of garden watering was found to be around 17min/watering. She also reported that houses with automatic sprinklers water the gardens at least 4 times a week while houses with hose and manual sprinklers water an average of 1.75 times per week. The “Water Resource Strategy” for Melbourne Water stated that the typical household water consumption for garden watering is 32kL/p/year (87L/p/day) which is 19% of the total water demand (Melbourne water 2001).

Water demand for garden watering is not dependent on the number of people in the house, rather it depends on the size of the garden beds and lawns. Roberts (2004) noted that for a house with both a large garden area and a lawn area, the water demand in summer was 132kL/year (361L/day) which was 2.5 times more (52kL/year) than that of both small garden and lawn area. The report revealed that about 40% household of the study area had a house of both small garden and lawn area. In addition, Roberts illustrated that for all garden types, the average demand for garden watering could be considered as 66kL/year (180L/day) during the summer season.

Results of the Gato (2006) study revealed that washing machines consume 127.4L/p/day household and per capita consumption was 40L/p/day. The study also noted a relationship between the size of the household and per capita consumption for water use in the laundry. This means with the increase in the number of people the water use has also be increased.

Nonetheless, (WELS 2004) noted that by using water efficient washing machines it would be possible to save 25600 mega litres of water per year. The study also asserted that 8.8% of water consumption reduction could be achieved between 2003 and 2016 if efficient washing machines are introduced.

Based on Gato's (2006) recommendation, 16 Litre per capita for day (Lpcd) and 40Lpcd were taken as demand for toilet and laundry use in this study. In addition to Gato (2006) study, Roberts (2004) also reported on garden water usage. Due to present Stage 3a water restrictions in Melbourne, garden watering is only permitted on two days of the week. Roberts (2004) reported that on average for all garden types the water use was around 69kL/year. This reported value was obtained based on data collected prior to water restrictions were in place where people could water the lawns and plants all 7 days of the week. However, it was assumed during that period the garden watering was carried out on a daily basis only for 6 months of the year.

Based on the above information the daily demand for garden water usage was 382L/day for the six months of the year. Under current water restrictions householders cannot water the lawns. Thus the current demand was assumed to be 50% of the water used under the pre-restriction period. To ensure compatibility with the prevailing restricted environment garden watering was considered to occur 2 days of the week for 6 months of the year from October to March. The annual water usage using this criteria was estimated to be 191L/day.

In summary, the following values were taken as Demand for water (D_t):

Toilet flushing - 16Lpcd (with or without water restriction)

Laundry use - 40Lpcd (with or without water restriction)

Garden watering - 191L/day (2 days a week for duration of 6 months under water restrictions)

Roof area connected with a tank is determined by the area of roof which will be used to collect rainwater in the tank. An average house of Melbourne has a roof area of 175 m^2 (Enviro Friendly 2007). As a result, it was decided to vary the roof area from 100 m^2 to 250 m^2. In addition, it was also considered that 100% of the roof area was connected to a tank.

Figure 3.5 depicts the layout of the water balance model considered in this analysis. It ismandatory to install a first flush device to ensure the quality of rainwater stored in the tank. In addition, it is assumed that if there is insufficient water in the tank, the water from the mains will be used as the backup supply (reticulated water supply) for using in the laundry and toilet.

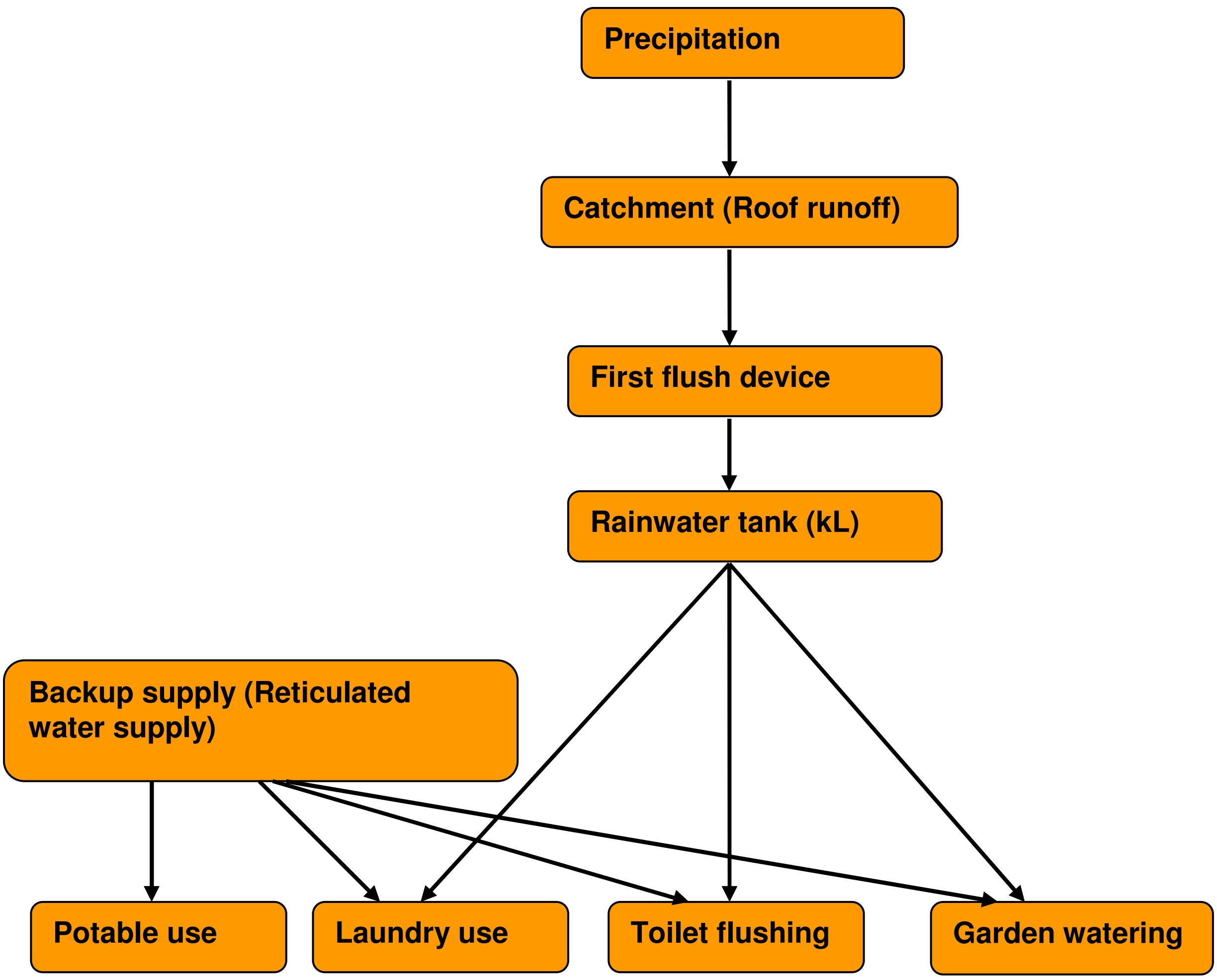

Figure 3.5 Schematic diagram of mapping rainwater supply for domestic use

3.6 Comparison with WSUD Model

As detailed in Chapter 2, WSUD (2005) developed guidelines to estimate rainwater tank sizes considering demand (toilet flushing), water supply reliability, roof area and MAR. It was decided to compare the tank sizes obtained as recommended in WSUD (2005) with the tank sizes calculated from the water balance model used in the current study. Tables 3.4, 3.5, 3.6 and 3.7 depict the comparison between the tank sizes for different reliabilities obtained from the two methods for a roof area between 100m^2 and 250m^2 for a household of 3 people in Melbourne (Mean rainfall = 660mm). The rainfall data of Hampton (MAR = 666mm) was used to carry out the analysis using the water balance model.

When the rainwater tanks are connected to roof areas between 150 m^2 to 250 m^2 the tank sizes vary marginally. This is not evident from the values given in Tables 3.5 to 3.7 as the tank sizes are given only as a one decimal point. Example of this above stated information has been shown in Figure 3.5 for Berwick which indicates that the variation in tank sizes for toilet demand is insignificant when the roof areas are between 150 m^2 to 250 m^2.

From the above results it is evident that there is a difference between the tanks sizes calculated from the two models. This variation could be due to

- The rainfall data used (More recent rainfall data were used in water balance model)
- Variation in the toilet demand value (WSUD (2005) considered toilet demand as 20Lpcd)

In addition, WSUD (2005) model only considers toilet flushing as the demand and hence limiting the use of the graphs developed for selection of optimal rainwater tank size. Hence, a new set of guidelines are required to calculate the tank size.

3.7 Relationship between tank size and reliability for different stations in the study area

One of the prime objectives of using of rainwater tanks is to conserve the mains water supply. In addition to the rainfall in the area, the tank size varies with the roof area, the demand for water considered and the reliability of supply. The supply reliability of the rainwater tank is extremely important for domestic water conservation as it reflects whether the tank will have sufficient water for daily use. In this study to supply domestic use the supply reliability of rainwater tanks in different parts of Melbourne was considered as a variable when sizing tanks. The curves in Figure 3.6 depict the relationship between the water supply reliability and size of the water tank from different roof sizes in Berwick, a suburb in South East

Melbourne (Figure 3.1). It is clear from these curves that the water supply reliability increases with the roof area (supply) for meeting the same demand.

The indoor demand for water varies with the number of occupants in a dwelling. Figures 3.7 and 3.8 depict the reliability and tank size for different demand types for three occupants in a house connected with a $100m^2$ and $250m^2$ roof areas respectively in Berwick. Similar results were obtained from other rainfall stations and roof sizes. The reliability of using the rainwater collected from the $100m^2$ roof size with a 2kL tank reduces from 95% to 76% when the water is used from toilet flushing to, laundry use. The result indicates that by using a small sized tank (2kL) connected with 100 m^2 roof area it is not possible to obtain considerable reliability (85%) if the tank is used for laundry use. Furthermore, if the water is used only for the laundry use, then a 5kL tank will have 85% reliability of supply.

Based on Figure 3.8 for attaining 85% reliability, the tank size varies from 2.9kL (toilet, and laundry) to 1.8kL (laundry). Hence, it can be stated that with a view to meeting higher demand a large tank is required for securing a high reliability. The differences in tank sizes to meet the same demand (eg toilet and garden, occupancy = 3 people) and from $100m^2$ roof size the impact of the spatial variability of the 10 stations are evident in Figure 3.8. Similar results were observed for the remaining 10 stations.

The MAR of these stations (Figure 3.9) vary from 45 mm to 1050mm. From Figure 3.8 it is evident that the supply reliability varies from 92% to 74% for a 1kL tank when one moves from Kinglake (MAR = 1054mm) to Werribee (MAR = 454 mm) to meet the toilet and garden demand for a roof size of $100m^2$. From the results of this figure it can be stated that water supply reliability depends on the rainfall of a particular location.

From the above figures it can be concluded that supply reliability strongly depends on demand, roof area as well as the mean annual rainfall (MAR) of the location. The information presented in Figures 3.6 to 3.9 is plotted on the Greater Melbourne map to assist the selection of a rainwater tank size for any location in Melbourne. Figures 3.10 to 3.12 show the variation in tank sizes for 90% reliability when rainwater is used for toilet and garden use from roof sizes of $100m^2$, $150m^2$ and $200m^2$ respectively. In addition, Figures 3.13 and 3.14 give the similar curves for the same demand and roof sizes with different water supply reliabilities (95% and 85%).

Table 3.4 Comparison between tank sizes obtained from the water balance model and recommended guidelines in WSUD (2005) (roof area $100m^2$)

Reliability	**Tank size (kL)**	
	Water Balance Model	**WSUD Model (2005)**
95%	0.9	1.9
90%	0.6	1.4
85%	0.4	0.8

Table 3.5 Comparison between tank sizes obtained from the water balance model and recommended guidelines in WSUD (2005) (roof area $150m^2$)

Reliability	**Tank size (kL)**	
	Water Balance Model	**WSUD Model (2005)**
95%	0.7	1.3
90%	0.5	0.8
85%	0.4	0.7

Table 3.6 Comparison between tank sizes obtained from water balance model and recommended guidelines in WSUD (2005) (roof area $200m^2$)

Reliability	**Tank size (kL)**	
	Water Balance Model	**WSUD Model (2005)**
95%	0.7	0.8
90%	0.5	0.7
85%	0.4	0.5

Table 3.7 Comparison between tank sizes obtained from water balance model and recommended guidelines in WSUD (2005) (roof area $250m^2$)

Reliability	**Tank size kL**	
	Water Balance Model	**WSUD Model (2005)**
95%	0.7	0.7
90%	0.5	0.5
85%	0.4	0.4

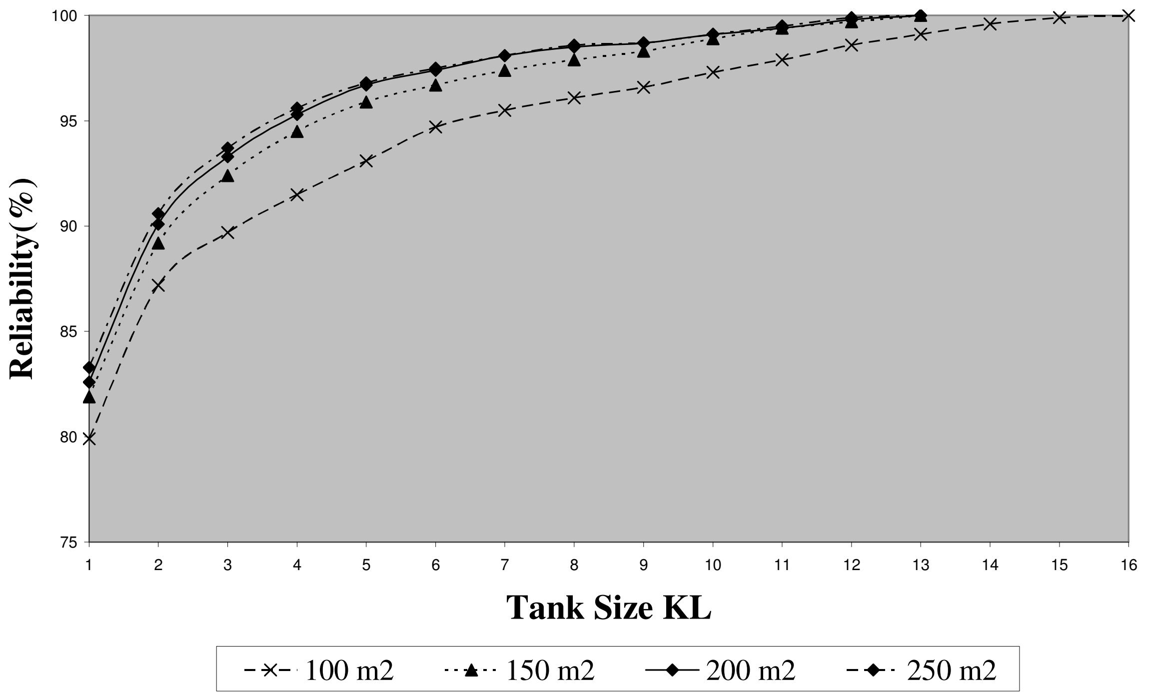

Figure 3.6 Relationship between the water supply reliability and tank size for different roof sizes in Berwick (Demand- toilet flushing only)

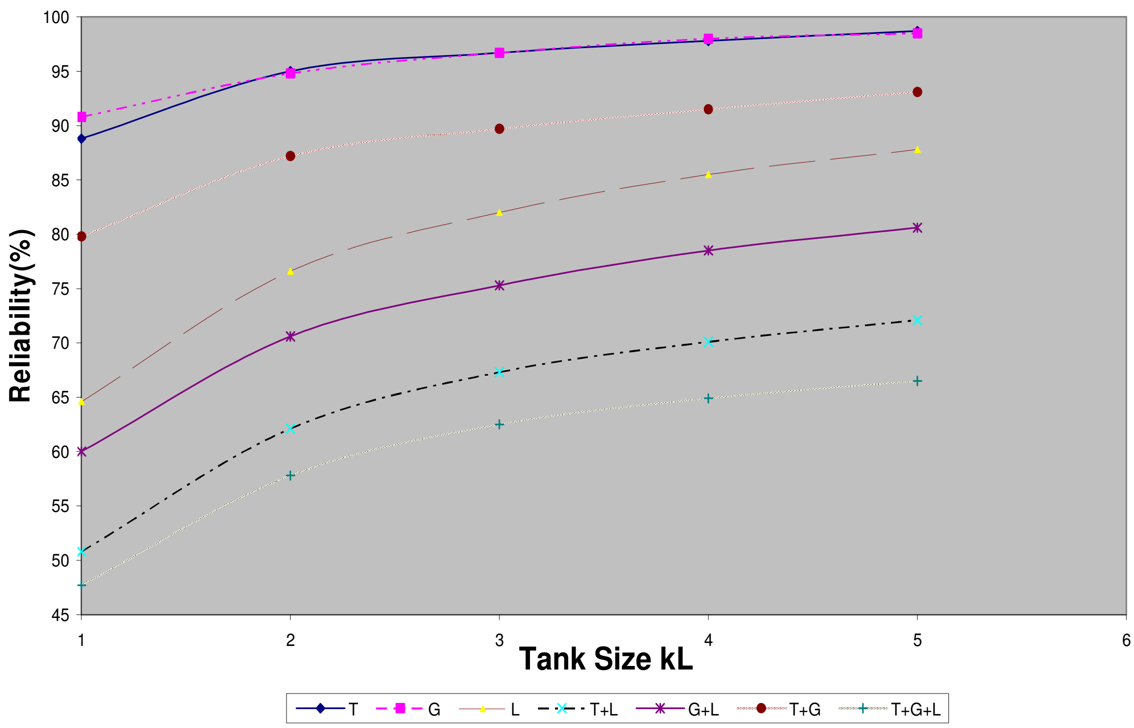

Figure 3.7 Relationship between the water supply reliability and tank size for different demand types from a dwelling with a 100m^2 roof area in Berwick . (T - toilet flushing; G - garden watering; L - laundry use)

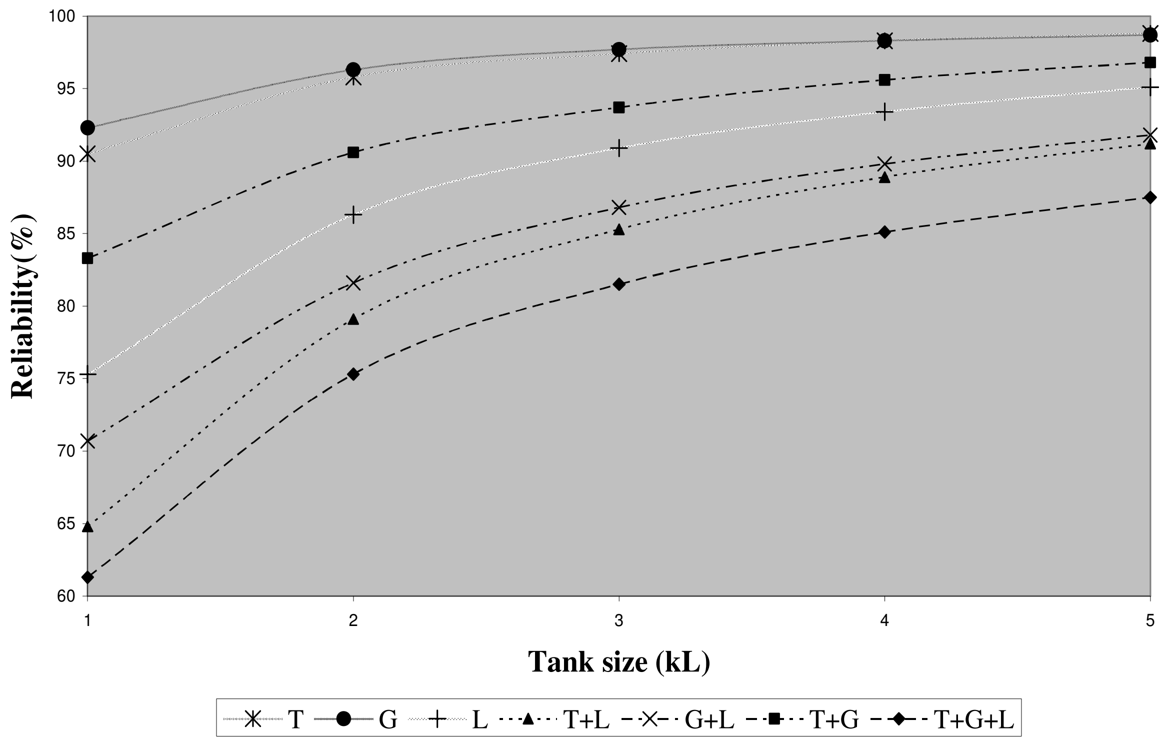

Figure 3.8 Relationship between the water supply reliability and tank size for different demand types from a dwelling with a 250m^2 roof area in Berwick

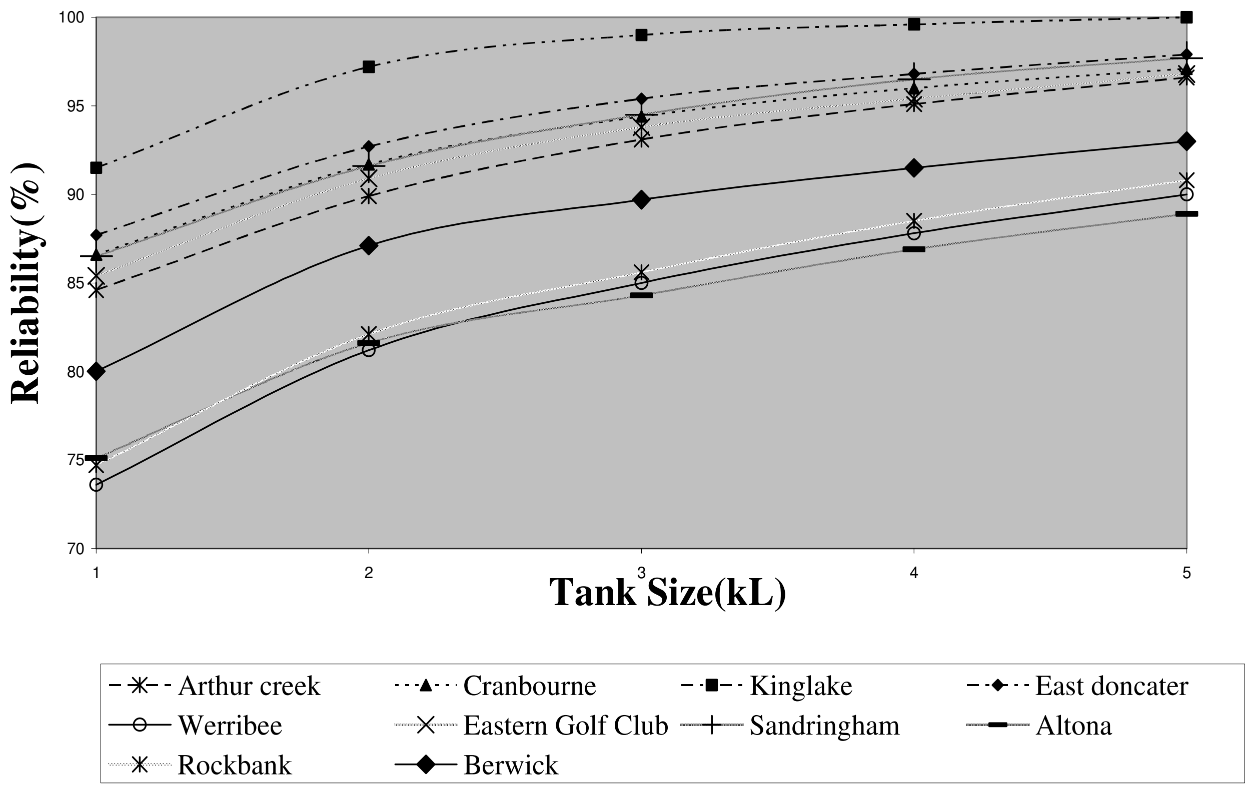

Figure 3.9 Relationship between the water supply reliability and tank size for 100 m^2 roof size and one demand type (toilet and garden use) for 10 different stations

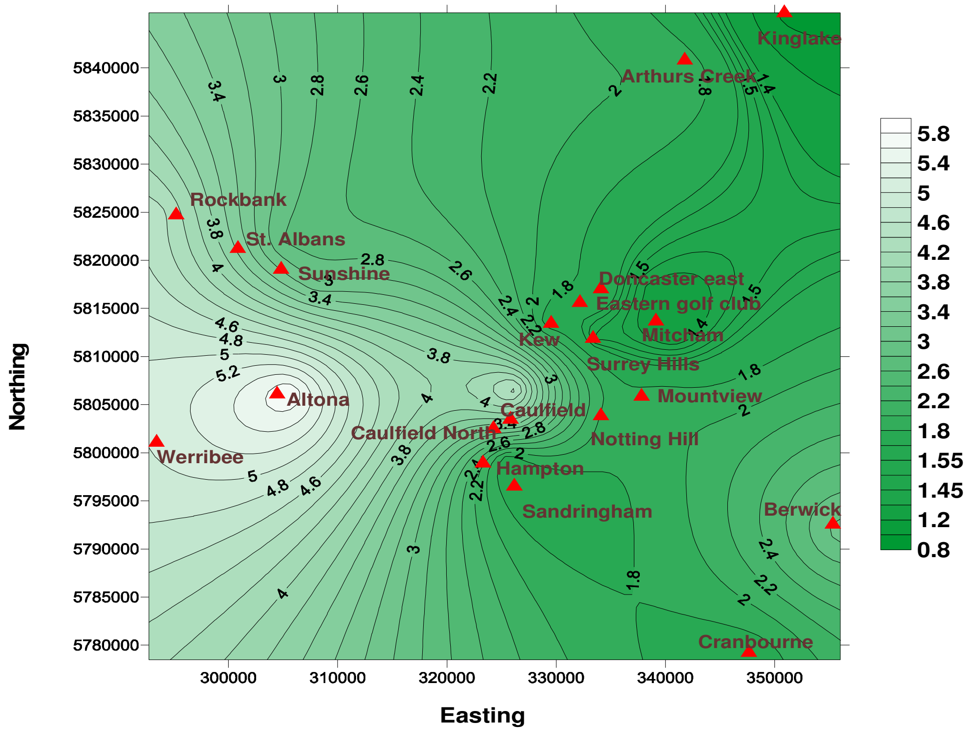

Figure 3.10 Variation of optimum tank sizes for a water supply reliability of 90% from a roof size of 100 m^2 with a water demand for toilet flushing and garden watering

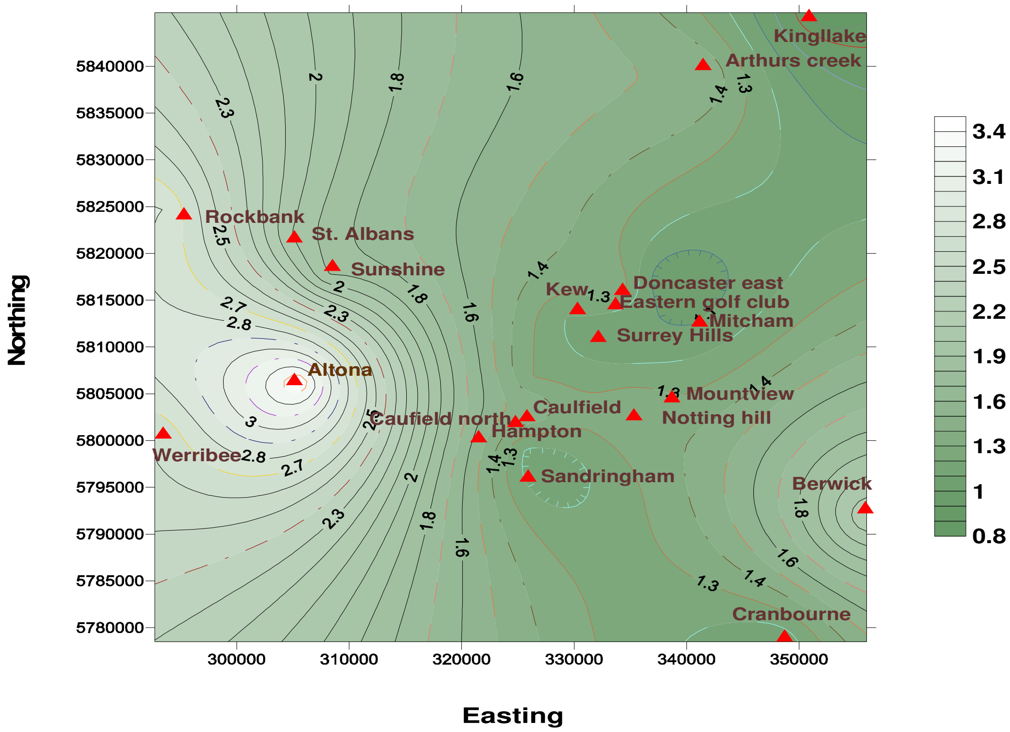

Figure 3.11 Variation of optimum tank sizes for a water supply reliability of 90% from a roof size of 150 m^2 with a water demand for toilet flushing and garden watering

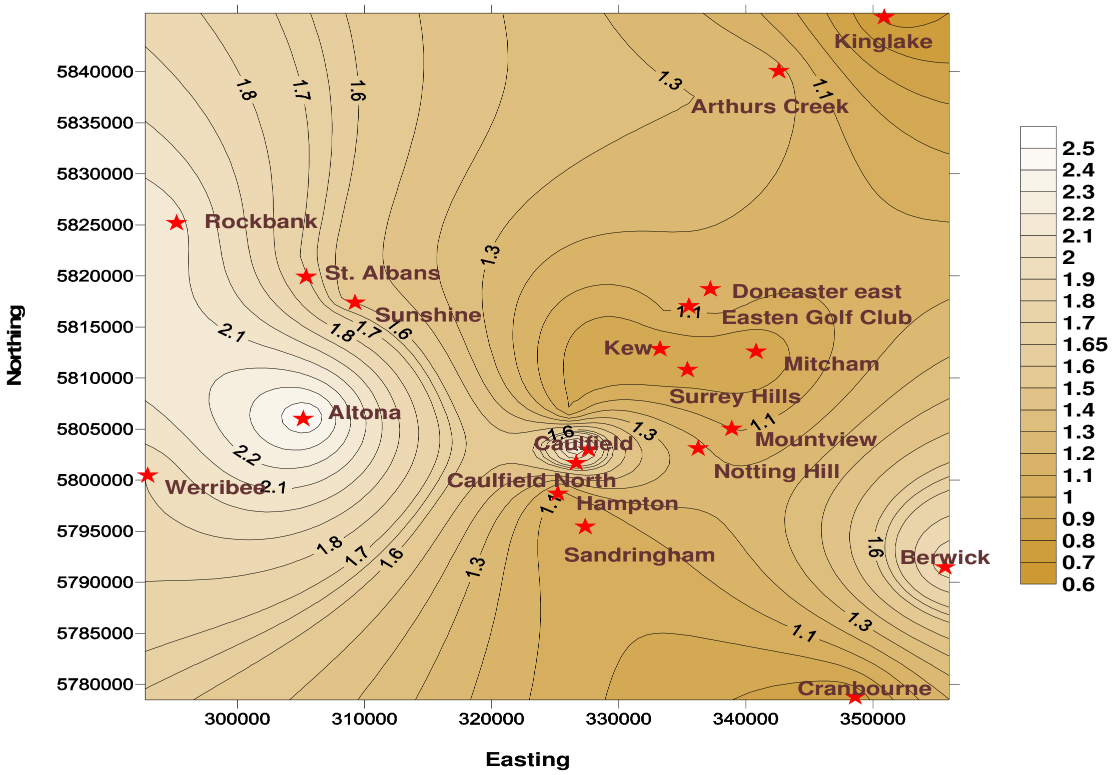

Figure 3.12 Variation of optimum tank sizes for a water supply reliability of 90% from a roof size of 200 m^2 with a water demand for toilet flushing and garden watering

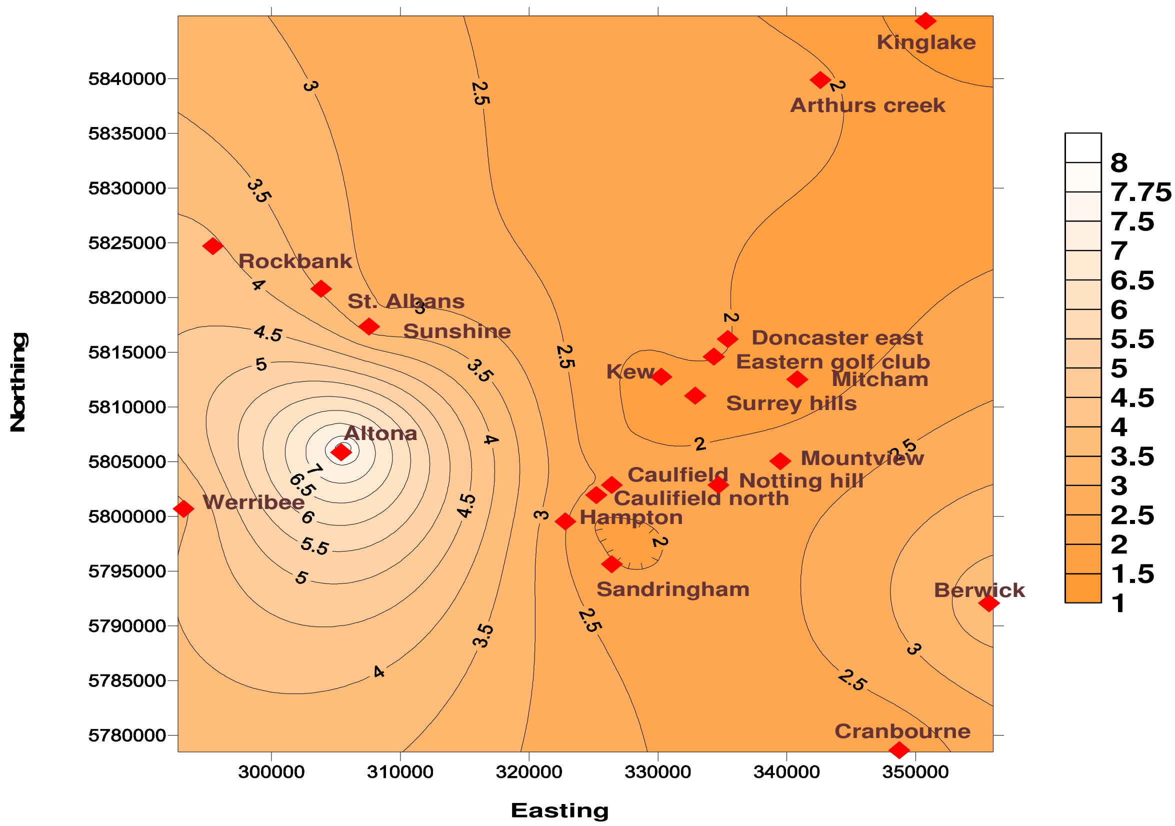

Figure 3.13 Variation of optimum tank sizes for a water supply reliability of 95% from a roof size of 200 m^2 with a water demand for toilet and garden use

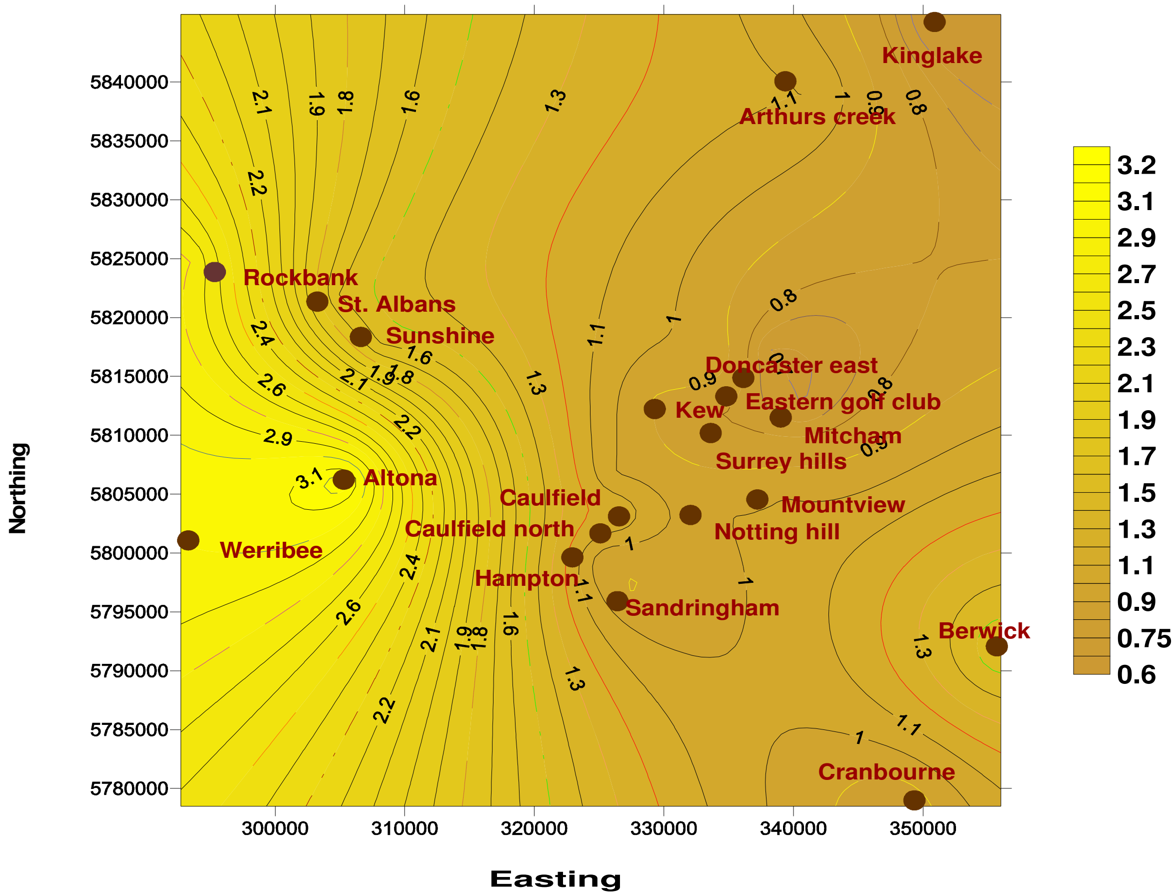

Figure 3.14 Variation of optimum tank sizes for a water supply reliability of 85% from a roof size of 100 m^2 with a water demand for toilet and garden us

From the above stated analysis it is evident that in addition to the distribution of rainfall, the roof area, demands for water and supply reliability are important factors considered in the selection of the optimum tank size. As such, a number of charts similar to above figures (Figures 3.10, 3.11, 3.12, 3.13 and 3.14) are necessary to select the optimal rainwater tank size to meet the customer's selected demand.

Although the mean rainfall values in Werribee, Rockbank and Altona are around 450mm, the optimum tank sizes vary from 5.8kL (Altona) to 4.4kL (Rockbank). Table 3.3 depicted the mean annual rainfall, number of rainy days, standard deviation and skewness values for above three rainfall stations. Although the average annual rainy days in these three stations are almost the same there is a significant variation in the skewness value which indicates the variation in the temporal pattern of rainfall. While analysing the rainfall data in Rockbank it was observed that there was a presence of considerable period with no rainfall in comparison with Altona and Werribee. Furthermore, there were few big rain events in Rockbank compared to other stations which explains the difference in the Co-efficient of Variation (CV) and skewness. Hence, it can be stated that in addition to mean annual rainfall, the rainfall distribution throughout the year is also important in computing of impacting the optimum tank size. However, due to complexity of the variation in the above statistical variable, only the spatial distribution of the mean annual rainfall of the stations was considered in determining the optimum rainwater tank size.

A potential customer of a rainwater tank also need to consider the cost of the rainwater tank and the area available for installing it before selecting the appropriate tank size. The variation of cost with the tank sizes will be reported in Chapter 6.

3.8 Spillage and usage of rainwater from a tank

In selecting the rainwater use, it is also important to minimize the spillage (or overflow) from the tank to maximize the usage. The demand for rainwater, the size of the tank, roof size and the location all have a direct impact on both spillage and usage. The customer may want to secure a reasonable reliability as well as minimize potable use. The percentage reduction of stormwater entering the drainage system was calculated using Equation 3.10. Rainfall volume was calculated by using Equation 3.11.

Percentage reduction in stormwater = Usage (kL)/Rainfall volume (m^3) *100% (3.10)

Rainfall volume (m^3) = Roof area (m^2) * Mean annual rainfall (m) (3.11)

Figure 3.15 depicts the spillage of rainwater by using a 3kL tank meeting different demands from a $100m^2$ roof area in Berwick. The figure reveals that maximum spillage occurs when the demand is at its lowest. As a result, utilisation will be maximised when the tank will be used to meet the combined maximum demand: toilet flushing, laundry use and garden watering.

For a typical household in Berwick of a roof size of $100m^2$ and a household of three people, Table 3.8 details the relationship between reliability, spillage, usage and tank size for a demand equal to of meeting toilet flushing, garden watering and laundry use needs. From the above table, it is evident that with the increase of tank size the ratio of spillage and usage will decrease which means that a large tank can accommodate more water which ensures high usage and reliability. The decision has to be taken by the potential user of the rainwater tank as to what the appropriate size of the tank is after considering the demand that is planned to meet, the reliability of supply, the cost and the land area that is available to install the tank. Table 3.9 further illustrates that with increase of mean annual rainfall, both reliability and usage of rainwater increase. This will be discussed further in detail in Chapter 5. The size of the rainwater tank should be optimized in such a way to ensure minimum spillage and maximum usage of rainwater stored in the tank. However, for low rainfall areas, even after using a large tank (as big as 5kL), it is not possible to secure considerable supply reliability of rainwater even for only laundry use because there is insufficient rainwater available to be stored in the rainwater tank.

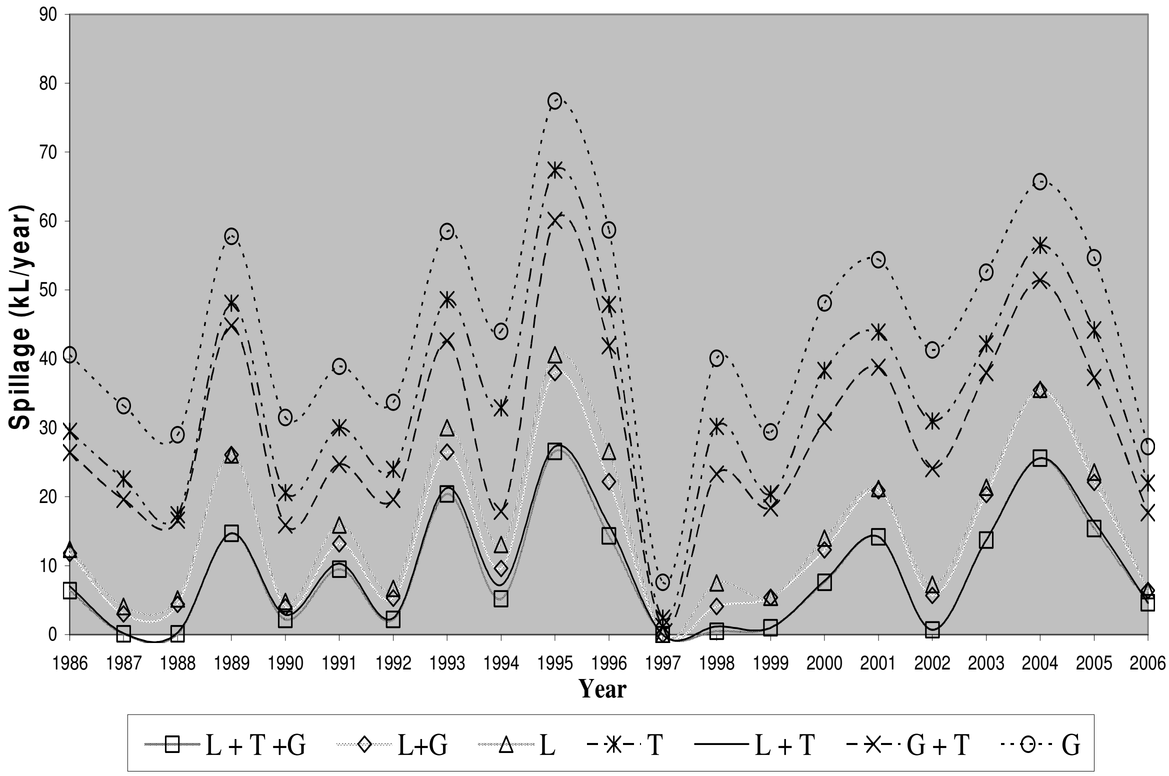

Figure 3.15 Spillage of rainwater for different demand and 100 m^2 roof area (Berwick)
(T – Toilet flushing; L – Laundry use; G – Garden watering)

Table 3.8 Spillage, Usage and Reliability relationship for different tank sizes (Berwick)

Tank Size (kL)	Spillage/Usage	Reliability (%)
1	0.59	47.9
2	0.32	57.8
3	0.22	62.5
4	0.17	64.9
5	0.14	66.5

Table 3.9 Relationship between reliability and usage of a 5 kL tank for laundry demand ($100m^2$ roof area)

Rainfall station	Reliability (%)	Usage (kL/year)
Werribee	62.7	25.9
Rockbank	65.6	28.1
Altona	66.1	26.9
Sunshine	73.0	30.9
St. Albans	74.6	30.0
Arthurs creek	89.2	37.9
Caulfield	89.1	38.8
Hampton	90.5	39.4
Kew	91.3	39.7
Sandringham	91.9	37.4
Mountview	98.9	43
Berwick	87.8	37.4
Caulfield North	93.7	40.8
Surrey Hills	93.4	40.6
Notting Hills	97.9	42.6
Eastern golf Club	91.7	39.1
East Doncaster	95.6	39.7
Cranbourne	94.7	40.3
Mitcham	96.6	41.1
Kinglake	99.7	41.3

Figures 3.16, 3.17 and 3.18 depict the variation of spillage, usage and reliability of supply of rainwater when tank sizes vary from 1kL to 5kL tanks in Berwick (MAR = 710mm), Werribee (MAR = 454mm) and Kinglake (MAR = 1054mm). The spillage, usage and supply reliability were calculated for low (garden), medium (toilet and garden) and high (toilet, garden and laundry) for a typical household size of 3 people from a roof size of $100m^2$. As given in Figure 3.16 the spill of rainwater is small in low MAR (Werribee) in comparison with high MAR (Kinglake). However, the usage (Figure 3.17) and supply reliability (Figure 3.18) are also low if the MAR is low. This indicates that majority of the time the water needs to be supplied from the mains pipelines to meet the demand in this area.

Based on values in Figure 3.18, a 5kL rainwater tank in the Kinglake area could fulfil the demand for laundry, toilet and garden with 89% water supply reliability. For the above demand on average only 20kL of water per year would spill. In the high rainfall Kinglake area a 5kL tank will give a 90% reliability of supply to meet the toilet, garden and laundry use.

However, in low mean annual rainfall areas similar to Werribee, it is important to select the tank size carefully depending on the planned for use of rainwater and preferred reliability of supply as there is a considerable variation in the above parameters. As given in Figure 3.16, the spill is small in low MAR in comparison with high MAR. However, as shown in Figure 3.18, the reliability of supply is very low (40%) even with a 5kL tank if the rainwater is being used for toilet flushing, laundry use and garden watering (high demand scenario). This indicates that 60% of the time water from the mains supply (potable water) is required to supplement tank water use. However, if the intended use of rainwater is only for the garden, 99% reliability could be achieved even in the low rainfall Western side of Melbourne. From the customer’s point of view, bigger the tank size, the spill will be reduced whilst usage and reliability kept high. However, there will be a cost versus reliability tradeoffs.

Installation of large tanks will further reduce the pressure on urban drainage infrastructure. However, this will add extra pressure on the user in the form of additional cost on the tank as well as the space needed to install the tank. Figure 3.19 depicts the variation of percentage reduction in volume of stormwater entering into urban drains when rainwater tank sizes vary from 1kL to 5kL. The water that flows in to urban drains could be reduced at least by 50% (Figure 3.19) of the current roof runoff if the rainwater is captured at least in 5kL size rainwater tanks and used in the laundry, toilet and garden use right across Greater Melbourne. These calculations are based on 100% uptake of rainwater tanks. This is only a hypothetical calculation as it is impossible to have 100% penetration of large water tanks across all Melbourne. The percentage reduction in stormwater runoff is low if the rainwater is used only for garden use. That is mainly because the existing Level 3a water restrictions in Melbourne which allows garden watering only 2 days of the week. Watering lawns is prohibited. The reduction of volume of stormwater reduces the stress on downstream drainage infrastructure. Rainwater tanks would further reduce the pressure on downstream infrastructure during storm event by providing storage for attenuation thus delaying peak flows.

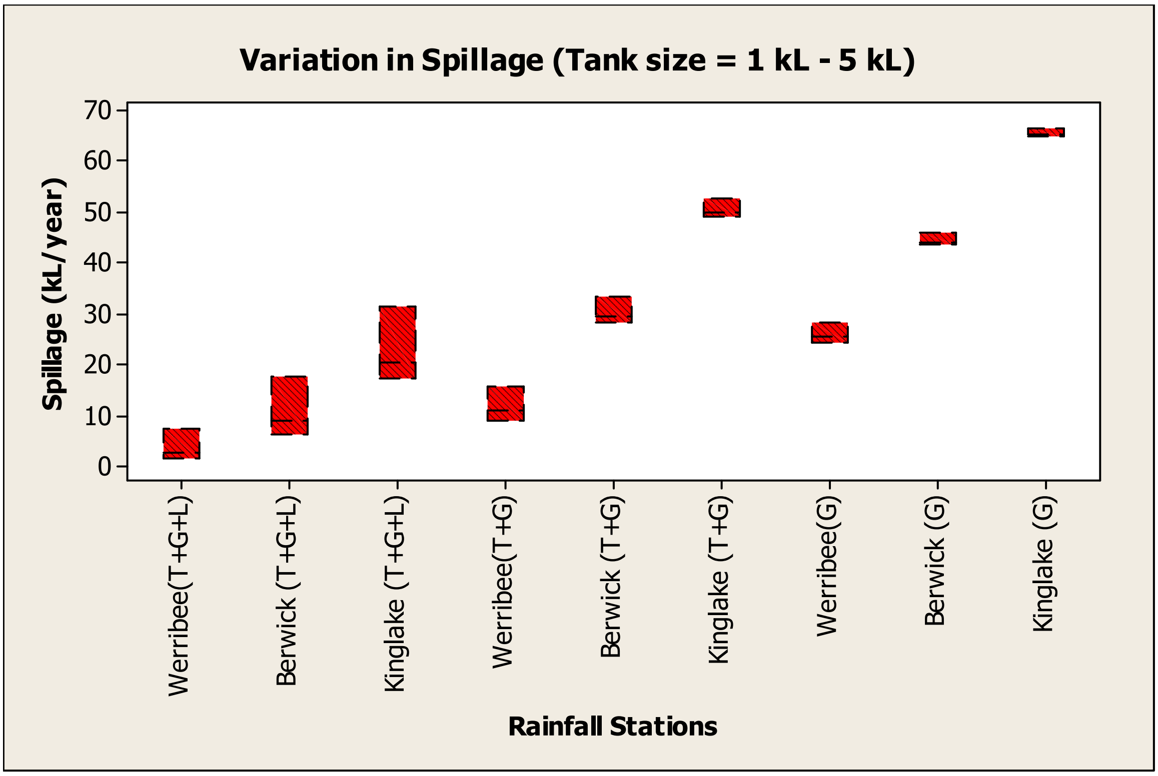

Figure 3.16 Spillage of rainwater from 1kL to 5kL tank sizes for a typical household (3 people) across Greater Melbourne (100m^2 roof area)

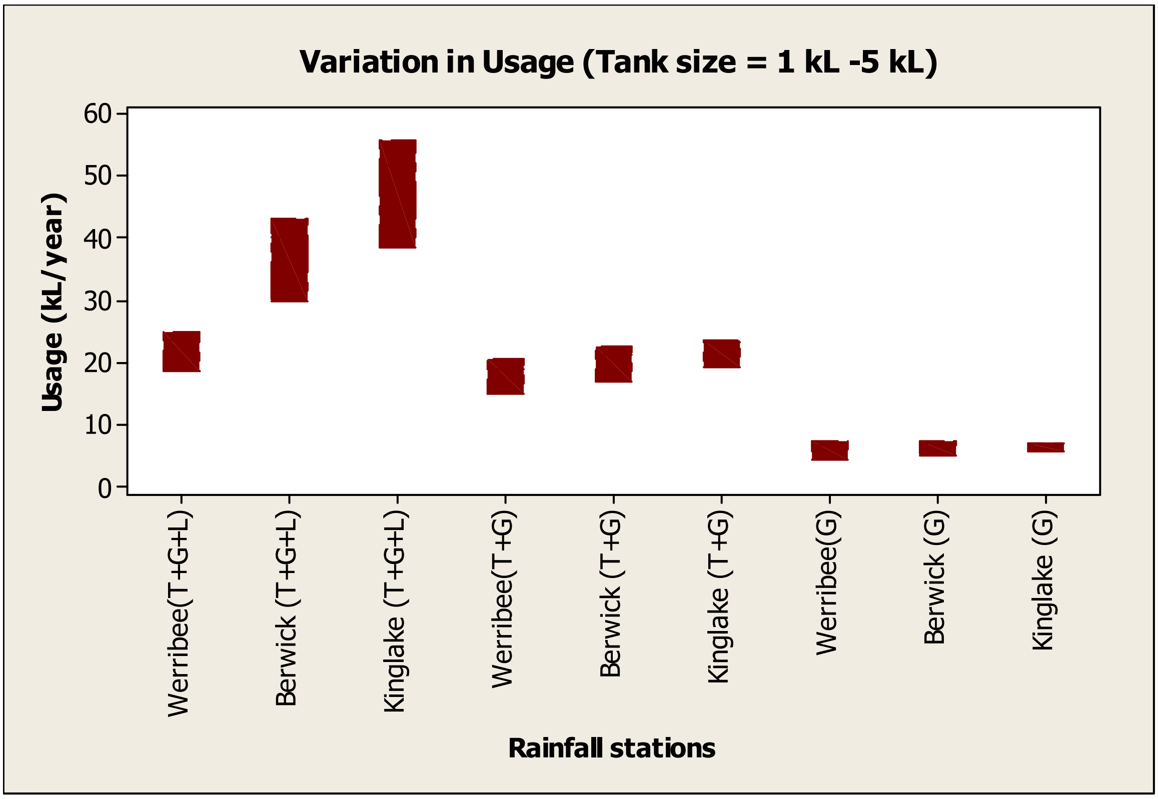

Figure 3.17 Usage of rainwater from 1kL to 5kL tank sizes for a typical household (3 people) across Greater Melbourne (100m^2 roof area)

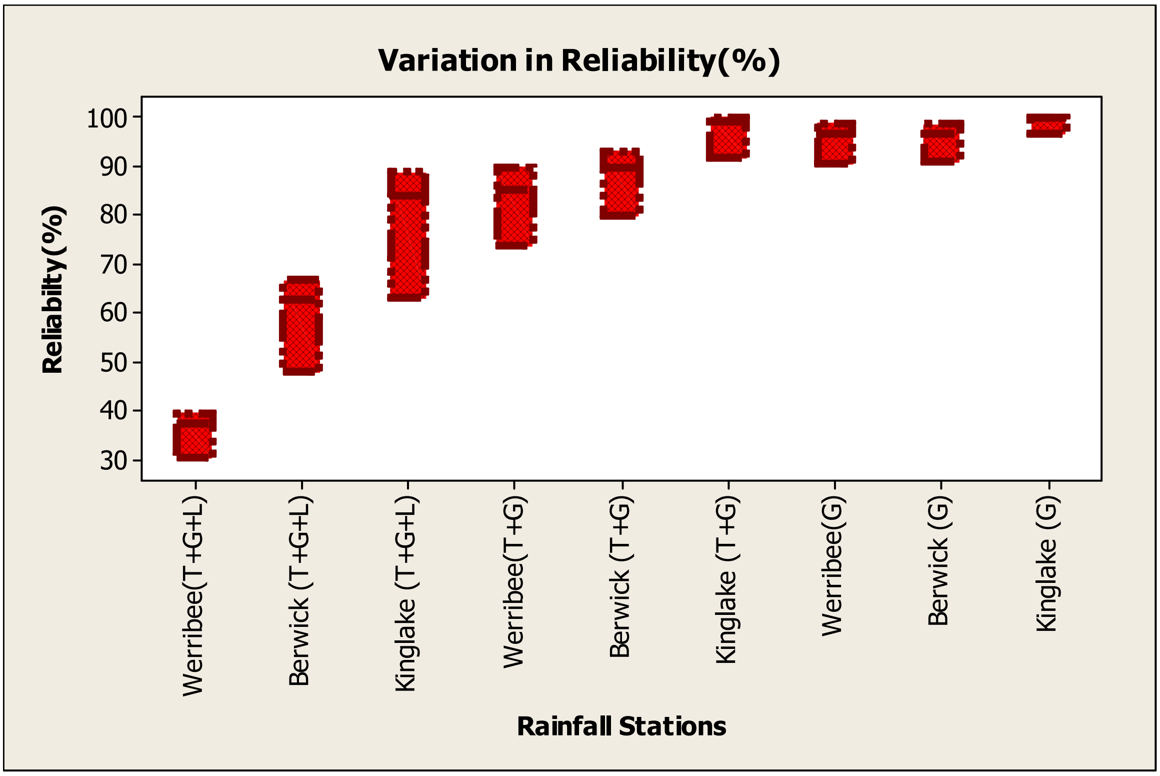

Figure 3.18 Reliability of tank sizes from 1kL to 5kL for a typical household (3 people) across Greater Melbourne (100m^2 roof area)

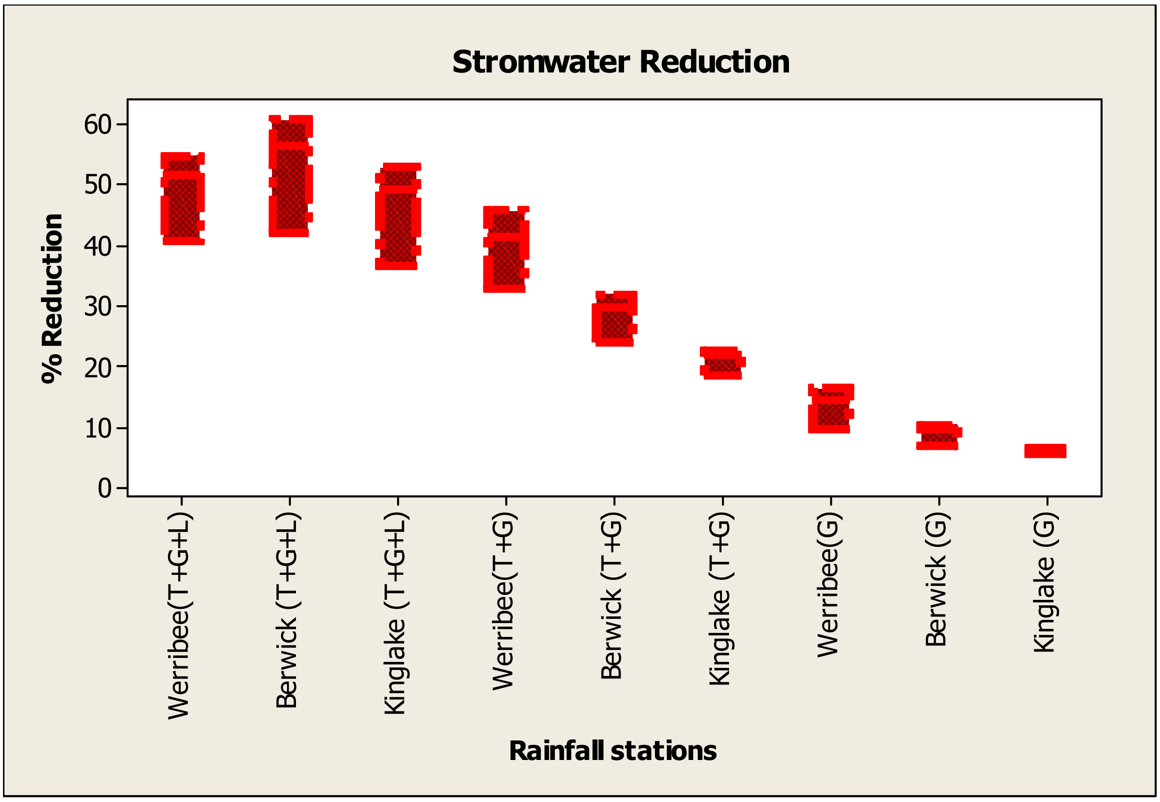

Figure 3.19 Percentage reduction of total volume of stormwater runoff for a typical household (3 people) across Greater Melbourne (100m^2 roof area)

3.9 Summary and conclusions

The model developed by Water Sensitive Urban Design (WSUD 2005) for selecting the optimum tank size for three different regions of Melbourne is inadequate in the present context considering the fact that those guidelines considered toilet flushing as the only demand supplied by tank water and the change in the rainfall pattern over the last 10 years. Due to application of Stage 3a water restrictions in Melbourne garden watering is permitted only for two days a week. As a result, a potential customer of rainwater tanks may first use the rainwater tank for garden watering only. On top of this, these guidelines did not consider the rainfall data of the last 10 years including 2006 which was the driest year in the last 100 years.

As reported in Chapter 2, Duncan and Wight (1991) developed a model to calculate rainwater tanks for domestic water supply in Melbourne area. One of the significant discrepancies of the model is the demand value used in this study. For instance, it was considered that for a 3 people household the water demand would be 520L/day which is wrong in the present context of stringent water restrictions and advanced water saving appliance use. As a result, a methodology was developed using a simple water balance model to effectively select the optimum tank size in the present context taking into consideration the rainfall data for the last 10 years (the driest years).

The rainfall pattern in Melbourne indicates that there is significant rainfall variability in the Greater Melbourne Region. Rainfall varied between 454mm in Werribee (West) to 1054 mm in Kinglake. The selection of the appropriate size of the rainwater tank is important to optimize the use of rainwater. The rainfall variability in Melbourne confirms that the 'one size fits all' approach is not optimal. This study contributes towards determining the optimum size of the rainwater tank taking into consideration variation of the rainfall within metropolitan Melbourne and the demand it could meet at different levels of reliability. A simple water balance model was developed to optimize the rainwater tank size taking into consideration the variation of roof area, occupancy, demand and daily rainfall at the location. The chapter analysed the impact of collecting catchment runoff for different volumes of rainwater tanks restricting the use to domestic use and some outdoor use only. Similar variability is expected in areas surrounding other major cities in Australia such as Sydney, Brisbane and Adelaide. The chapter shows that to meet the same demand (toilet and garden use), and to achieve the same supply reliability (90%), the tank size required in the western side of Melbourne is as high as 7 times what is required in the north-east side. Based on the mean annual rainfall in western side of Melbourne, it is not possible to harvest rainwater in sufficient volume to be used both indoors and outdoors unless a number of very large rainwater tanks (as big as 50kL) are installed. This is not practical due to cost and space limitations to install large rainwater tanks. Furthermore, for a 1kL tank the water supply reliability varied from 74% to 92% for different locations stations across Melbourne considering the demand for toilet flushing and garden watering from a 100m^2 roof size. A potential user also needs to predetermine what demand one wants to satisfy garden (external) or internal use (toilets only or toilet and laundry both) prior to selecting the appropriate size. Moreover, the user also needs to appreciate the concept of reliability as there are significant costs related tradeoffs to be made prior to purchasing a rainwater tank. As a result, the optimal sizes of a rainwater tank should be determined after considering the geographic location in Melbourne, daily rainfall, roof size, intended use of rainwater and the supply reliability desired.

In areas with sufficient mean annual rainfall (700mm/year) the rainwater could be harvested effectively for domestic purposes to meet laundry demand with a high reliability (above 85%) of supply. In low rainfall areas, almost all rainwater could be harvested for indoor use. This will reduce the stormwater volume that flows into the drains at least by 30% even if the tank sizes are as small as 1kL. The reduction in the volume of stormwater reduces the stress on downstream drainage infrastructure especially on stormwater treatment infrastructure such as wetlands. As a result, it will have significant impact on environment and ecology. Rainwater tanks would further reduce the pressure on downstream infrastructure during a storm event by providing storage for attenuation. The chapter concludes that it is mandatory to closely examine the spillage (wastage) and usage behaviour for the desired reliability before selecting an appropriate tank size for domestic use.

The rainfall pattern in and around metropolitan Melbourne indicates that there is significant variability within the west being 450mm and 1050mm in the East. To facilitate this it is necessary to develop a large numbers of graphs based on roof area, expected demand and supply reliability for different locations of Melbourne. This will not be user friendly. As a result, the preference is for a generalized curve that will consider all the above stated parameters to select the optimum tank size in Melbourne. The development of the generalized curve is elaborated in Chapter 4.

Chapter 4

Development Of A Methodology To Calculate Optimum Tank Size

4.1 Introduction

As reported in Chapter 3, there is a significant variation in MAR across Melbourne if one travels from west to north and east. As a result, there will be a considerable variation in rainwater tanks sized to meet the same demand for a similar roof area in different parts of Melbourne. Hence, the "one size fits" all philosophy is not applicable in Melbourne when selecting the optimum tank size.

Optimum tank size selection depends on a number of parameters such as: roof area, expected demand, rainfall and supply reliability. As such, a number of charts developed for a particular area similar to Figures 3.9, 3.10 and 3.11 are necessary to select the optimal rainwater tank size to meet the customer's needs. It was decided to use a dimensionless curve type analysis with all above variables with a view to reducing the number of independent variables in the analysis. These dimensionless numbers were used to develop a set of curves to obtain the optimum tank size depending on the location, the demand for rainwater use, the roof area and the reliability of supply.

This chapter presents the dimensionless analysis and the advancements made in the methodology to obtain the optimum tank size.

4.2 Derivation of dimensionless numbers

4.2.1 Dimensionless analysis

In 1915 Buckingham developed Buckingham π theorem to derive dimensionless variables from a set of independent variables (Crowe et al 2007). Equation 4.1 gives the number of dimensionless numbers that could be obtained from a set of independent variables.

$$\text{Number of dimensionless variables, } \pi = n - m \tag{4.1}$$

where,

n = The number of independent parameters

m = The basic dimensions in the independent parameters

Crowe et al (2007) stated that there are two methods to carry out the dimensionless analysis.

1. Step by step method
2. Exponent method

In this study the exponent method was used to carry out the dimensionless analysis. The characteristics of this method are that after identifying the significant variables, a set of algebraic simultaneous equations are solved. These equations were derived from the requirement of dimensional homogeneity of equations describing the physical systems.

Exponent Method

Following parameters were considered when developing dimensionless numbers in this study.

- Tank capacity (C) m^3
- Annual water demand (D) m^3/ year
- Roof area (A) m^2
- Mean annual rainfall, (R) mm/year
- Supply reliability (Re) %

The dimensions of above variables are:

$[C] = L^3$, $[D] = \frac{L^3}{T}$, $[A] = L^2$, $[R] = \frac{L}{T}$, [Re] = % (dimensionless)

where,

L = length and T = time

Based on Equation 4.1,

Number of independent parameters (n)	= 5
Number of dimensionless number (m)	= 2
No. of dimensionless variables π	= 3

However, dimensionless homogeneity requires

$$[C] = [D^a A^b R^c], \qquad (4.2)$$

where, a, b & c are coefficients

$$[L^3] = [(\frac{L^3}{T})^a (L^2)^b (\frac{L}{T})^c] \quad (4.3)$$

Equating the power of L and T on each side of the equation results in two algebraic equations.

L: 3 = 3a+2b+c (4.4)

T : 0 = -a- c (4.5)

From Equations 4.4 and 4.5 it is distinct that there are two equations but three unknowns. Nevertheless, two of the unknowns can be solved in terms of third unknown. For selecting the third unknown it is considered which exponent is appearing more frequently in the above two equations. Let us assume that b and c will be solved in terms of a. The new equations are:

$$b = \frac{3-2a}{2} \quad (4.6)$$

$$c = -a \quad (4.7)$$

Now, these exponents are substituted back in the combination of the physical variables and the result is

$$[C] = [(D)^a (A)^{(\frac{3-2a}{2})} (R)^{-a}] \quad (4.8)$$

or

$$C = A^{\frac{3}{2}} (\frac{D}{AR})^a \quad (4.9)$$

The dimension of $A^{\frac{3}{2}}$ is same as of tank capacity and will be common to every term in the function. Moreover, the combination $(\frac{D}{AR})$ is dimensionless.

Thus Equation 4.9 can be rewritten as

$$C = A^{\frac{3}{2}} f(\frac{D}{AR}) \quad (4.10)$$

$$\frac{C}{A^{\frac{3}{2}}} = f(\frac{D}{AR}) \quad (4.11)$$

Based on the dimensionless homogeneity concept each term will be a function (*f)* of the tank capacity. Hence, the variables in each term must combine in such a way that the combination has the dimension of Tank capacity (C). The derived dimensionless numbers are:

$\pi_1 = \dfrac{C}{A^{\frac{3}{2}}}$, $\pi_2 = \dfrac{D}{AR}$ and π_3= Reliability

4.2.2 Relationship between dimensionless numbers

Rainwater tank sizes were calculated using the water balance model for each station with different demand types and from different roof sizes whilst varying the supply reliability between 85% to 95%. The mean annual rainfall at selected stations across Melbourne varied between 450mm to 1050mm. As legislated by the Victorian Government, the rainwater could be used for toilet flushing, laundry use and for outdoor garden watering. The demand for rainwater was calculated using following combinations.

- Toilet only
- Garden only
- Laundry only
- Toilet and laundry
- Toilet and Garden
- Laundry and Garden
- Toilet , garden and laundry

Furthermore, the demand was calculated by varying the number of people in the dwelling between 1 to 3. The typical garden size was fixed at 350m^2 (Roberts 2004). The roof size of an individual household was varied between 100m^2 to 250m^2 in establishing relationships between C, R, D, A and supply reliability. Dimensionless numbers were calculated for each separate station with different combinations of D, A and tank sizes obtained from Equation 4.11. The tank sizes were limited to a maximum of 20kL as the study concentrates on determining the optimum tank size for domestic use. However, a tank size of more than 5kL is considered large for an average house. It was decided to take tank sizes up to 20kL as rainwater demand in commercial buildings could be similar to domestic use adjusted to the number of people.

Rainwater tanks of bigger than 20kL were obtained under following conditions.

- Small roof areas (100m^2 – 150m^2) in low rainfall areas.
- High demand (Laundry and above) in low rainfall areas.

However, the threshold was fixed at 20kL.

Figures 4.1 to 4.3 illustrate the relationship between dimensionless numbers (π_1 and π_2) for Berwick, Caulfield North and Notting Hill respectively. Similar results were obtained for all other stations.

Regression relationships were developed between π_1 and π_2 using exponential, linear and power equations. Tables 4.1, 4.2 and 4.3 depict the regression relationships and the coefficient of determination (R^2) for each curve at each location for 95%, 90% and 85% reliabilities respectively. From the above Tables it can be observed that for majority of the stations R^2 values are greater than 70%. A low R^2 values of 39%, 52% and 23% were obtained from exponential, linear and power relationships for the Caulfield station with 95% supply reliability (Table 4.1). Although the information in rainfall characteristics at Caulfield (Table 3.3) is the same as for many other stations the rainwater tank sizes obtained were bigger than 20kL for a supply reliability of 95%. As mentioned earlier the tank sizes greater than 20kL were not used to develop regression relationships.

Based on the R^2 values it was decided to use the exponential regression relationship as the best-fit curve. Figures 4.1, 4.2 and 4.3 depict the exponential curves fitted to points obtained for Berwick, Caulfield North and Notting Hill stations. Curves from the remaining 17 stations are given in Appendix A, Figures A1 to A17.

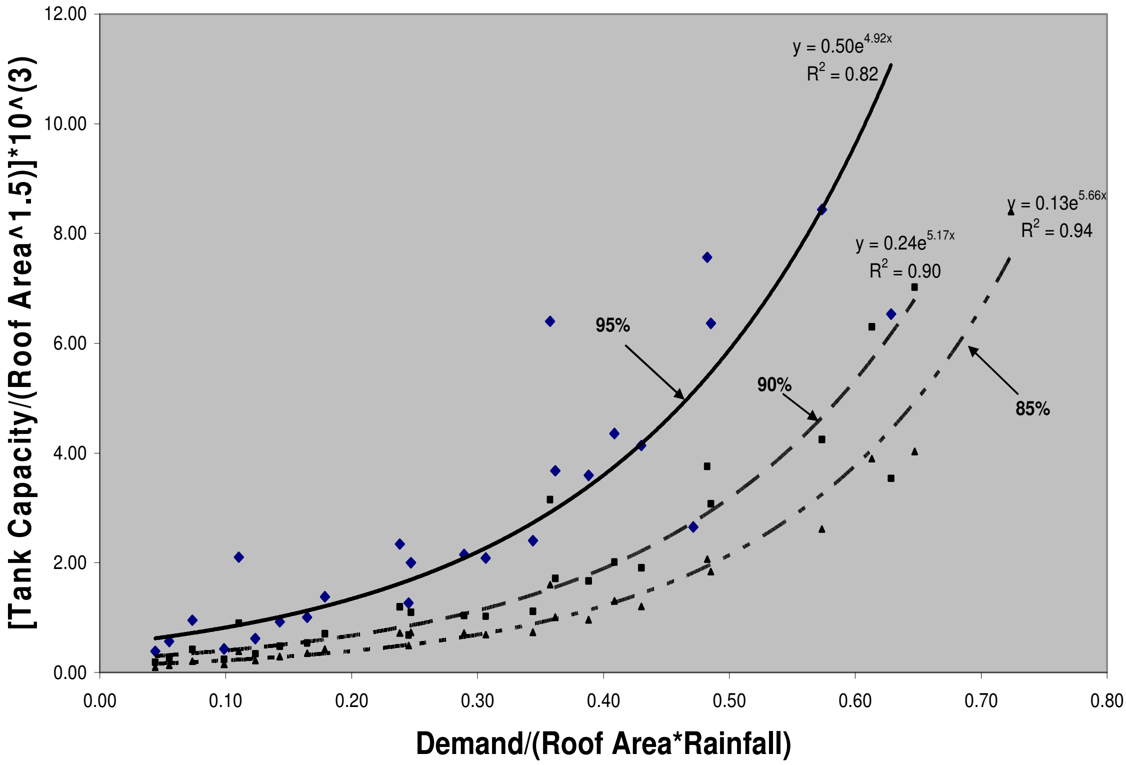

Figure 4.1 Relationship between dimensionless numbers for D, A and MAR for different water supply reliabilities for Berwick

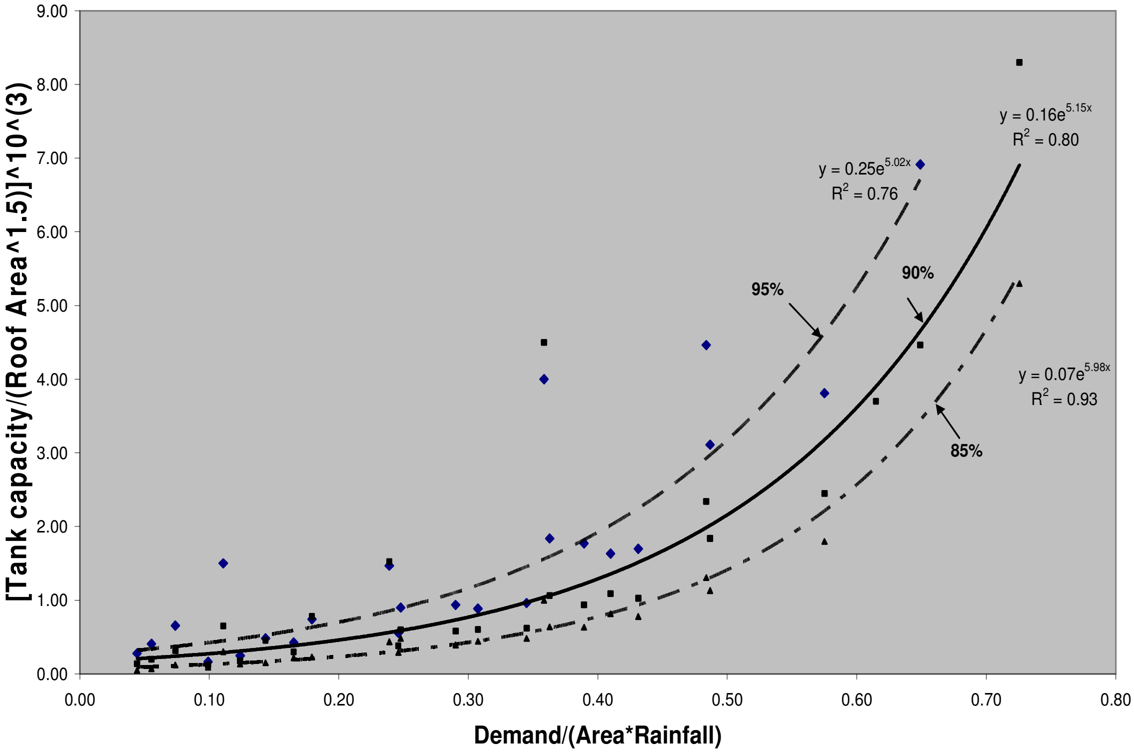

Figure 4.2 Relationship between dimensionless numbers for D, A and MAR for different water supply reliabilities for Caulfield North

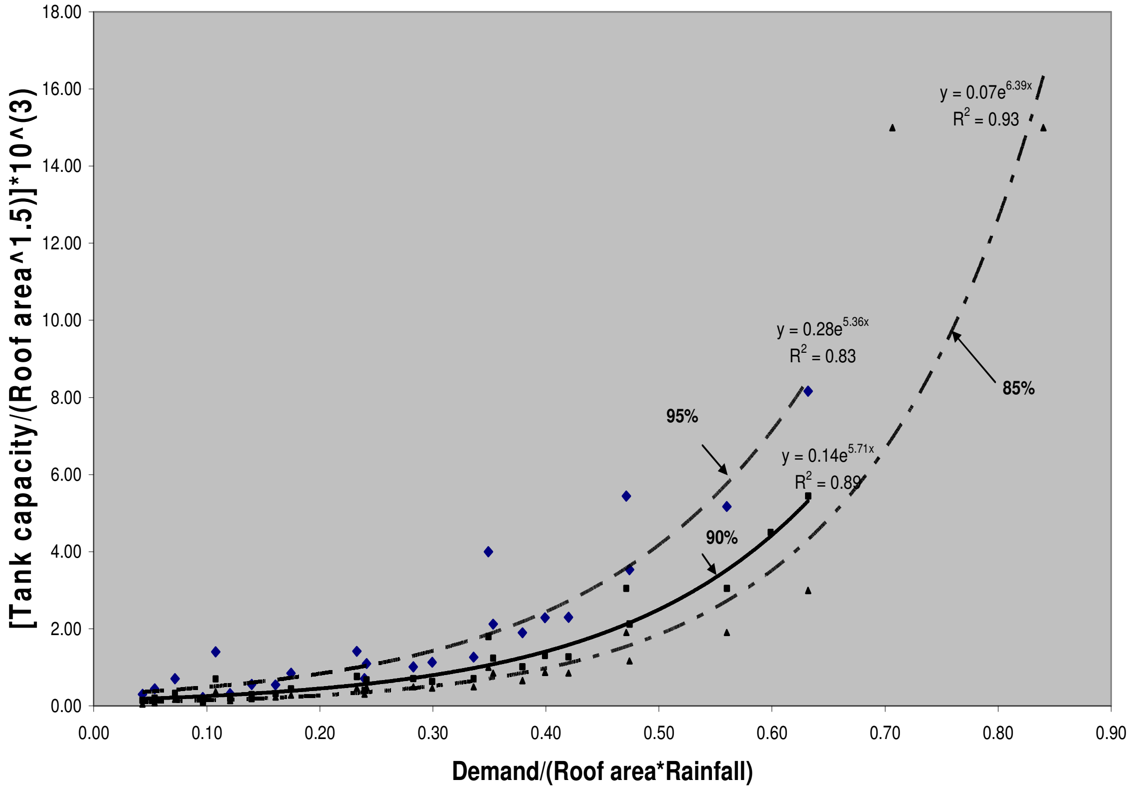

Figure 4.3 Relationship between dimensionless numbers for D, A and MAR for different water supply reliabilities for Notting Hill

Table 4.1: Regression equations between the two dimensionless numbers with a 95% supply Reliability

Station	Exponential		Linear		Power	
	Equation	R^2	Equation	R^2	Equation	R^2
Altona	$\pi_1 = 0.68\ e^{5.8\pi_2}$	0.58	$\pi_1=18.9\ \pi_2 -0.79$	0.70	$\pi_1 = 12.8\ \pi_2^{1.00}$	0.47
Arthur creek	$\pi_1 = 0.26\ e^{4.55\pi_2}$	0.82	$\pi_1=8.52\ \pi_2-0.92$	0.76	$\pi_1 = 5.03\ \pi_2^{1.09}$	0.82
Berwick	$\pi_1 = 0.50\ e^{4.92\pi_2}$	0.82	$\pi_1=12.48\pi_2-0.64$	0.76	$\pi_1 = 10.45\ \pi_2^{1.10}$	0.82
Caulfield	$\pi_1 = 2.07\ e^{2.38\pi_2}$	0.39	$\pi_1=20.17\ \pi_2+0.39$	0.52	$\pi_1 = 7.84\ \pi_2^{0.42}$	0.23
Caulfield North	$\pi_1 = 0.25\ e^{5.03\pi_2}$	0.76	$\pi_1=8.19\ \pi_2- 0.66$	0.69	$\pi_1 = 5.16\ \pi_2^{1.06}$	0.65
Cranbourne	$\pi_1 = 0.23\ e^{5.22\pi_2}$	0.81	$\pi_1=11.48\ \pi_2-1.36$	0.67	$\pi_1 = 6.06\ \pi_2^{1.46}$	0.69
East Doncaste	$\pi_1 = 0.17\ e^{5.72\pi_2}$	0.72	$\pi_1=6.43\ \pi_2-0.45$	0.66	$\pi_1 = 3.87\ \pi_2^{1.03}$	0.62
Eastern golf club	$\pi_1 = 0.27\ e^{5.24\pi_2}$	0.84	$\pi_1=9.67\ \pi_2-0.89$	0.73	$\pi_1 = 6.38\ \pi_2^{1.12}$	0.75
Hampton	$\pi_1 = 0.21\ e^{5.32\pi_2}$	0.83	$\pi_1=10.97\ \pi_2-1.42$	0.71	$\pi_1=4.58\ \pi_2^{0.95}$	0.69
Kew	$\pi_1 = 0.20\ e^{5.46\pi_2}$	0.82	$\pi_1=10.8\ \pi_2-1.36$	0.69	$\pi_1 = 5.92\ \pi_2^{1.20}$	0.68
Kinglake	$\pi_1 = 0.25\ e^{5.20\pi_2}$	0.84	$\pi_1=10.31\ \pi_2-0.97$	0.68	$\pi_1=4.58\ \pi_2^{0.95}$	0.70
Mitcham	$\pi_1 = 0.22\ e^{5.43.\pi_2}$	0.81	$\pi_1=9.54\ \pi_2- 0.98$	0.66	$\pi_1=5.09\ \pi_2^{1.03}$	0.67
Mountview	$\pi_1 = 0.21\ e^{5.89\pi_2}$	0.88	$\pi_1=17.81\pi_2- 2.71$	0.65	$\pi_1=9.39\ ^{1}\ \pi_2^{.37}$	0.76
Notting Hill	$\pi_1 = 0.28\ e^{5.36\pi_2}$	0.83	$\pi_1=10.42\pi_2- 0.93$	0.74	$\pi_1 = 6.67\ \pi_2^{1.10}$	0.72
Rockbank	$\pi_1 = 0.33\ e^{4.521\pi_2}$	0.76	$\pi_1=10.18\ \pi_2-1.06$	0.73	$\pi_1 = 7.80\ \pi_2^{1.26}$	0.69
Sandringham	$\pi_1 = 0.33\ e^{4.49\pi_2}$	0.76	$\pi_1=8.41\ \pi_2-1.20$	0.85	$\pi_1 = 5.34\ \pi_2^{0.99}$	0.66
St. Albans	$\pi_1 = 0.27\ e^{4.99.\pi_2}$	0.81	$\pi_1=10.68\ \pi_2-1.20$	0.75	$\pi_1 = 7.61\ \pi_2^{1.25}$	0.72
Sunshine	$\pi_1 = 0.24\ e^{4.89\pi_2}$	0.87	$\pi_1=10.15\ \pi_2-1.35$	0.75	$\pi_1 = 6.87\ \pi_2^{1.27}$	0.75
Surrey Hills	$\pi_1 = 0.18\ e^{5.58\pi_2}$	0.85	$\pi_1=12.6\ \pi_2- 1.81$	0.63	$\pi_1 = 6.07\ \pi_2^{1.24}$	0.70
Werribee	$\pi_1 = 0.27\ e^{5.14\pi_2}$	0.84	$\pi_1=13.66\pi_2-1.90$	0.73	$\pi_1 = 9.81\ \pi_2^{1.42}$	0.76

** π_1= Tank Capacity/ (Roof Area^1.5)*10^(3); π_2 = Demand/ (Roof Area* Rainfall)

Table 4.2: Regression equations between two dimensionless numbers with a 90% supply Reliability

Station	Exponential		Linear		Power	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
Altona	$\pi_1 = 0.22\ e^{5.5\,\pi_2}$	0.83	π_1=9.34 π_2-0.96	0.77	π_1=6.70 $\pi_2^{1.26}$	0.72
Arthur creek	$\pi_1 = 0.14\ e^{4.74x}$	0.85	π_1=6.16 π_2-0.86	0.65	π_1=3.58 $\pi_2^{1.22}$	0.78
Berwick	$\pi_1 = 0.24\ e^{5.18\,\pi_2}$	0.90	π_1=8.79 π_2-0.84	0.79	π_1=6.66 $\pi_2^{1.23}$	0.87
Caulfield	$\pi_1 = 0.44\ e^{4.98\,\pi_2}$	0.75	π_1=12.86π_2-0.91	0.74	π_1=10.3 $\pi_2^{1.18}$	0.76
Caulfield North	$\pi_1 = 0.16\ e^{5.16\,\pi_2}$	0.80	π_1=7.65 π_2-0.89	0.62	π_1=4.68 $\pi_2^{1.24}$	0.73
Cranbourne	$\pi_1 = 0.11\ e^{5.51\,\pi_2}$	0.91	π_1=9.33 π_2-1.54	0.67	π_1=4.48 $\pi_2^{1.36}$	0.79
East Doncaster	$\pi_1 = 0.09\ e^{6.12\,\pi_2}$	0.88	π_1=6.65 π_2-0.84	0.61	π_1=3.61 $\pi_2^{1.26}$	0.77
Eastern golf club	$\pi_1 = 0.14\ e^{5.41\,\pi_2}$	0.90	π_1=8.11 π_2-1.14	0.66	π_1=4.34 $\pi_2^{1.25}$	0.78
Hampton	$\pi_1 = 0.13\ e^{5.06\,\pi_2}$	0.86	π_1=5.79 π_2-0.71	0.69	π_1=3.44 $\pi_2^{1.18}$	0.75
Kew	$\pi_1 = 0.10\ e^{5.55\,\pi_2}$	0.96	π_1=5.44 π_2-0.86	0.66	π_1=3.42 $\pi_2^{1.24}$	0.67
Kinglake	$\pi_1 = 0.14\ e^{5.47\,\pi_2}$	0.86	π_1=6.08 π_2-0.55	0.71	π_1=3.13 $\pi_2^{1.04}$	0.76
Mitcham	$\pi_1 = 0.12\ e^{5.53\,\pi_2}$	0.90	π_1=8.11 π_2-1.13	0.66	π_1=3.77 $\pi_2^{1.21}$	0.75
Mount view	$\pi_1 = 0.13\ e^{5.75\,\pi_2}$	0.91	π_1=9.02 π_2-1.28	0.72	π_1=5.55 $\pi_2^{1.38}$	0.83
Notting Hill	$\pi_1 = 0.14\ e^{5.71\,\pi_2}$	0.89	π_1=7.02 π_2-0.77	0.77	π_1=4.62 $\pi_2^{1.23}$	0.80
Rockbank	$\pi_1 = 0.17\ e^{4.77\,\pi_2}$	0.88	π_1=7.5 π_2-1.09	0.77	π_1=5.60 $\pi_2^{1.42}$	0.80
Sandringham	$\pi_1 = 0.16\ e^{4.98\,\pi_2}$	0.86	π_1=8.41π_2-1.2	0.85	π_1=4.05 $\pi_2^{1.17}$	0.74
St. Albans	$\pi_1 = 0.14\ e^{5.18\,\pi_2}$	0.88	π_1=6.34 π_2-0.76	0.78	π_1=4.66 $\pi_2^{1.32}$	0.79
Sunshine	$\pi_1 = 0.16\ e^{4.66\,\pi_2}$	0.87	π_1=5.71π_2-0.68	0.76	π_1=4.03 $\pi_2^{1.247}$	0.78
Surrey Hills	$\pi_1 = 0.11\ e^{4.68\,\pi_2}$	0.61	π_1=11.9 π_2-2.43	0.44	π_1=4.06 $\pi_2^{1.58}$	0.85
Werribee	$\pi_1 = 0.13\ e^{5.48\,\pi_2}$	0.91	π_1=11.89 π_2-2.30	0.60	π_1=7.23 $\pi_2^{1.60}$	0.82

** π_1= Tank Capacity/ (Roof Area^1.5)*10^(3); π_2= Demand/ (Roof Area* Rainfall)

Table 4.3: Regression equations between two dimensionless numbers with a 85% supply Reliability

Stations	Exponential		Linear		Power	
	Equation	R^2	Equation	R^2	Equation	R^2
Altona	$\pi_1=0.12e^{5.73\pi_2}$	0.92	$\pi_1=7.87\pi_2-1.16$	0.75	$\pi_1=5.66\pi_2^{1.49}$	0.83
Arthur creek	$\pi_1=0.07e^{5.27\pi_2}$	0.94	$\pi_1=6.19\pi_2-1.17$	0.66	$\pi_1=2.78\pi_2^{.42}$	0.86
Berwick	$\pi_1=0.13\ e^{5.66\pi_2}$	0.94	$\pi_1= 7.74\pi_2-1.06$	0.70	$\pi_1=5.14\pi_2^{1.38}$	0.91
Caulfield	$\pi = 0.34\ e^{5.31\pi_2}$	0.84	$\pi_1=12.16\pi_2-1.12$	0.70	$\pi_1=8.60\pi_2^{1.17}$	0.77
Caulfield North	$\pi_1= 0.07e^{5.98\pi_2}$	0.93	$\pi_1= 4.85\pi_2- 0.67$	0.64	$\pi_1=3.03\pi_2^{1.38}$	0.89
Cranbourne	$\pi_1=0.06e^{5.89\pi_2}$	0.96	$\pi_1=5.73\pi_2-0.95$	0.70	$\pi_1=3.28\pi_2^{1.511}$	0.90
East Doncaster	$\pi_1=0.06e^{6.49\pi_2}$	0.96	$\pi_1=6.70\pi_2- 1.07$	0.62	$\pi_1=3.44\pi_2^{1.44}$	0.87
Eastern golf club	$\pi_1=0.07e^{5.90\ \pi_2}$	0.94	$\pi_1= .98\ _2-0.69$	0.74	$\pi_1=3.49\pi_2^{1.44}$	0.91
Hampton	$\pi_1=0.07e^{5.74\pi_2}$	0.93	$\pi_1=10.31\pi_2-0.97$	0.77	$\pi_1=4.58\pi_2^{0.96}$	0.90
Kew	$\pi_1=0.06e^{6.08\pi_2}$	0.96	$\pi_1=5.44\pi_2-0.86$	0.66	$\pi_1=3.40\pi_2^{1.52}$	0.90
Kinglake	$\pi_1=0.09e^{6.05\pi_2}$	0.91	$\pi_1=4.03\ \pi_2-0.35$	0.84	$\pi_1=2.80\ \pi_2^{1.20}$	0.90
Mitcham	$\pi_1 =0.07e^{6.0\ \pi_2}$	0.94	$\pi_1=5.01\pi_2-0.68$	0.72	$\pi_1=3.15\ \pi_2^{1.40}$	0.91
Mount View	$\pi_1 =0.06e^{6.18\pi_2}$	0.95	$\pi_1=5.70\pi_2-0.85$	0.71	$\pi_1=3.89\pi_2^{1.53}$	0.92
Notting Hill	$\pi_1 =0.07e^{6.39\pi_2}$	0.93	$\pi_1=14.26\pi_2-2.70$	0.56	$\pi_1=5.32\pi_2^{1.58}$	0.83
Rockbank	$\pi_1=0.08e^{5.28\pi_2}$	0.94	$\pi_1=6.70\ \pi_2-1.08$	0.72	$\pi_1=4.50\pi_2^{1.64}$	0.90
Sandringham	$\pi_1=0.09e^{5.46\pi_2}$	0.90	$\pi_1=5.15\pi_2-0.73$	0.68	$\pi_1=3.15\ \pi_2^{1.34}$	0.85
St. Albans	$\pi_1=0.12e^{4.81\pi_2}$	0.84	$\pi_1=6.02\pi_2-0.92$	0.63	$\pi_1=3.32\ \pi_2^{1.25}$	0.71
Sunshine	$\pi_1=0.08e^{5.24\pi_2}$	0.95	$\pi_1=7.03\pi_2-1.38$	0.51	$\pi_1=3.62\pi_2^{1.49}$	0.84
Surrey Hills	$\pi_1=0.06\ e^{6.33\pi_2}$	0.97	$\pi_1=7.07\pi_2-1.30$	0.42	$\pi_1=3.20\pi^{1.42}$	0.60
Werribee	$\pi_1=0.08e^{5.68\pi_2}$	0.95	$\pi_1=7.42\pi_2-1.40$	0.65	$\pi_1=5.14\pi_2^{\ 1.70}$	0.88

** π_1= Tank Capacity/ (Roof Area^1.5)*10^(3); π_2= Demand/(Roof Area* Rainfall

4.3 Development of a generalized curve to obtain the optimum tank size

In order to obtain a single dimensionless curve for selecting the optimum rainwater tank size it was later decided to combine the data points from all the stations. Data from randomly selected 16 stations were used to develop the combined curve. The other four stations were selected as independent stations to verify the accuracy of the developed equations. The R^2 values of power, linear and exponential regression equations (Equations 4.12 to 4.20) were compared when selecting the best form of the dimensionless curve. Figure 4.4 depicts the relationship between the tank size and the dimensionless numbers for three different reliabilities (95%, 90% and 85%).

Power equation:

95% reliability: $Y = 6.21\, X^{1.068}$, $R^2 = 0.62$ (4.12)

90% reliability: $Y = 4.68\, X^{1.2437,}$ $R^2 = 0.73$ (4.13)

85% reliability: $Y = 3.85X^{1.4138,}$ $R^2 = 0.78$ (4.14)

Linear equation

95% reliability: $Y = 10.04X - 0.84$ $R^2 = 0.64$ (4.15)

90% reliability: $Y = 7.81X - 0.95$, $R^2 = 0.61$ (4.16)

85% reliability: $Y = 6.71X - 1.05$, $R^2 = 0.52$ (4.17)

Exponential equation

95% reliability: $Y = 0.29\, e^{4.85X}$ $R^2 = 0.77$ (4.18)

90% reliability: $Y = 0.15e^{5.16X}$ $R^2 = 0.84$ (4.19)

85% reliability: $Y = 0.08\, e^{5.58X}$ $R^2 = 0.89$ (4.20)

From above power, linear and exponential equations, the best Coefficient of Determination (R^2) value was obtained from the exponential regression relationships.

The standard form of an exponential curve is given by Equation 4.21.

$$Y = a\, e^{bX} \tag{4.21}$$

a & b are empirical constants

Y = Dimensionless number $\pi_1 = \dfrac{C}{A^{\frac{3}{2}}}$

X = Dimensionless number $\pi_2 = \dfrac{D}{AR}$

C = Tank size (kL)

D = Demand (L/yr)

A= Roof area (m^2)

R = Mean annual rainfall (mm/yr)

Equation 4.21 in the log scale is a straight line and given in Equation 4.22

$$\log Y = \log a + b\,X \tag{4.22}$$

A graph of log Y vs. X (Figure 4.5) is a straight line with log a and b being the intercept of the vertical axis and b being the gradient of the line respectively.

Figures 4.4 and 4.5 represent the best fit exponential regression curves in normal scale and log scale respectively. The prime advantage of obtaining a straight line instead of a curve is that the values could be easily extrapolated if required.

By using the above exponential equations for different reliabilities, tank sizes were calculated for each dependent and independent station with different roof sizes and demand types. A potential tank user will be able to select the appropriate tank size by using this curve if the value of the roof area, demand and mean annual rainfall of that particular area is known. As an example, assume a potential customer of a rainwater tank that lives in the southern side of Greater Melbourne where the mean annual rainfall is around 700mm. The user decides the desired reliability to be at 95%. For the above customer, based on Figure 4.4, for a roof area of 200m^2 and a household of 3 with a designed demand to meet toilet flushing, garden watering and laundry use, the optimum tank size would be 9kL with 95% supply reliability. This may be too large from an aesthetic point of view. However, for the same household, if the desired demand is only for toilet and garden use for attaining 95% reliability, the tank size will be 2kL. In addition, for the same household and the desired demand (toilet + garden) the tank size would be 1.1kL for 90% reliability. From the above information, it can be stated that from a single generalized curve, the optimum tank size could be obtained based on desired reliabilities and demands (variabilities are for the customer to decide).

4.4 Verification of the developed curve

The exponential regression equations developed for 95%, 90% and 85% supply reliabilities (Equations 4.18, 4.19 and 4.20) were used to calculate the tank sizes at each location for different roof sizes and demand types. These values were compared with the tank sizes calculated from the water balance equation and are given in Figure 4.6. Tables 4.4, 4.5 and 4.6 and Figures 4.7, 4.8, 4.9 and 4.10 depict the regression relationships between the tank sizes calculated from the water balance equation and the generalized curve for 95%, 90% and 85% reliability respectively for each station used to develop the curve (dependent stations). Curves for the remaining 12 stations for different reliabilities and the goodness of fit parameters are shown in Appendix B (B1 to B12).

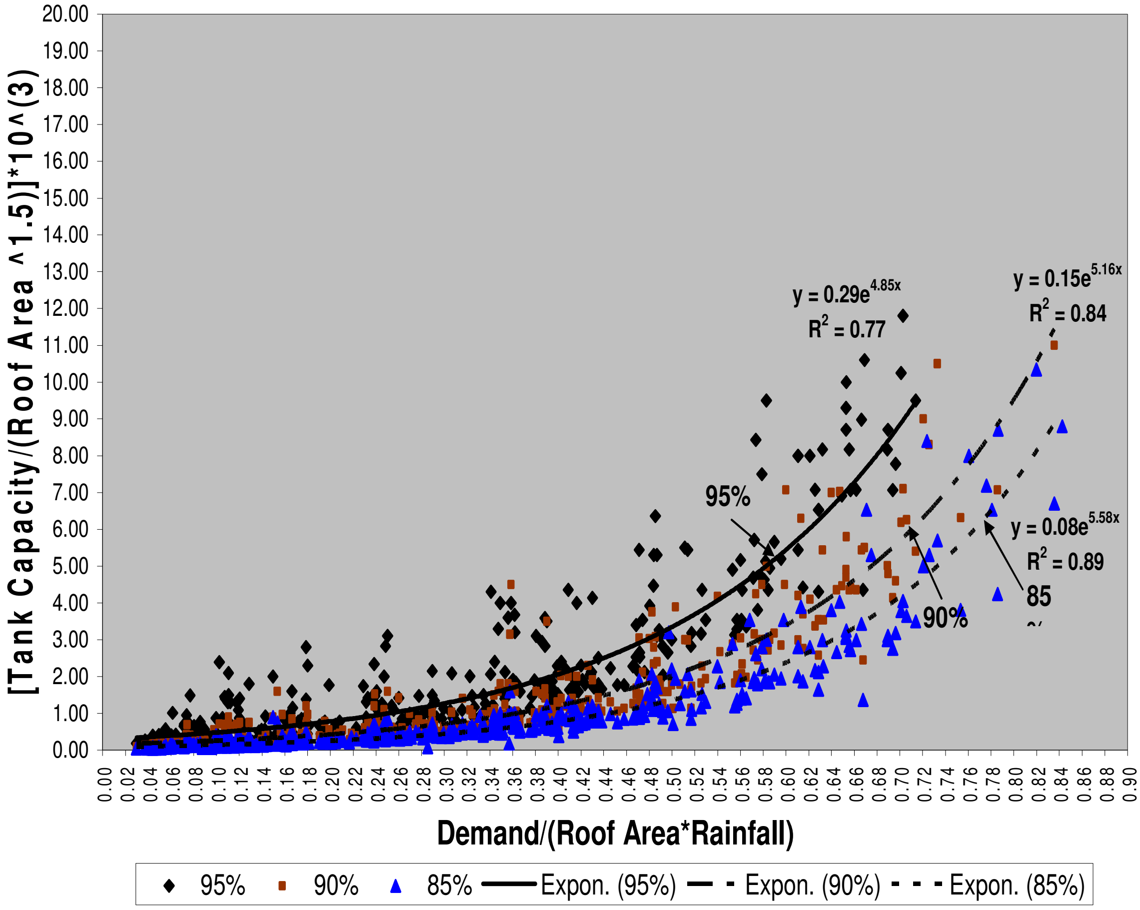

Figure 4.4: Exponential regression relationships between dimensionless numbers for 95%, 90% & 85% supply reliabilities

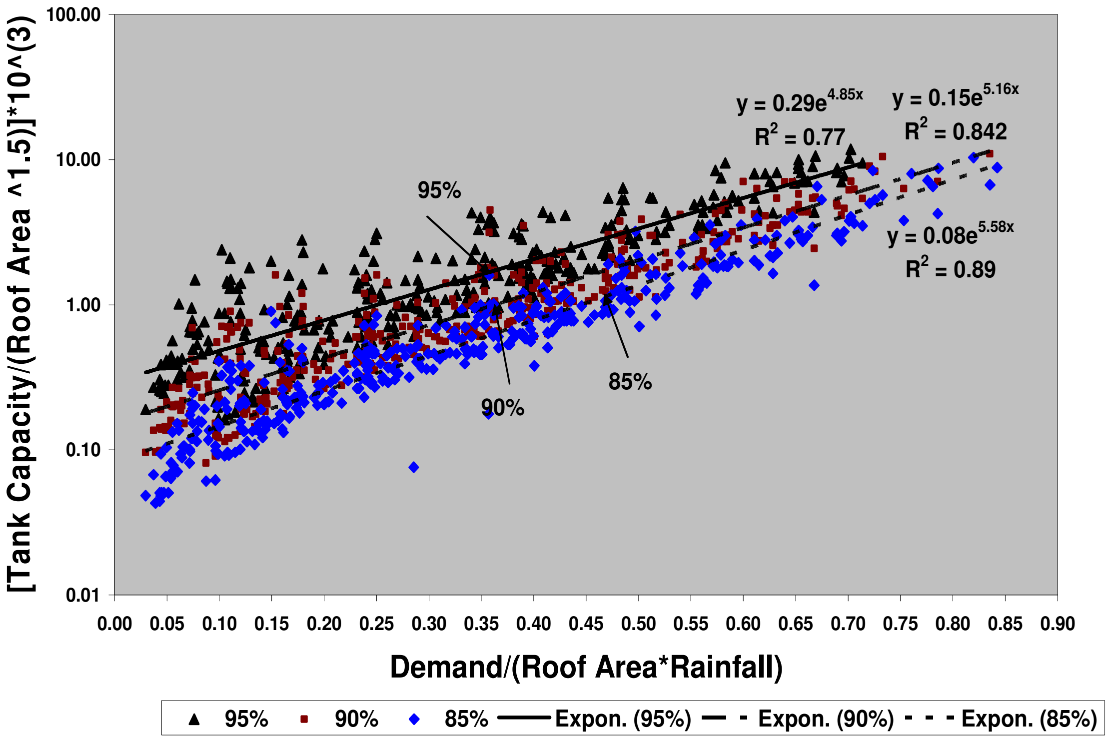

Figure 4.5: Exponential regression relationships between dimensionless numbers for 95%, 90% & 85% supply reliabilities

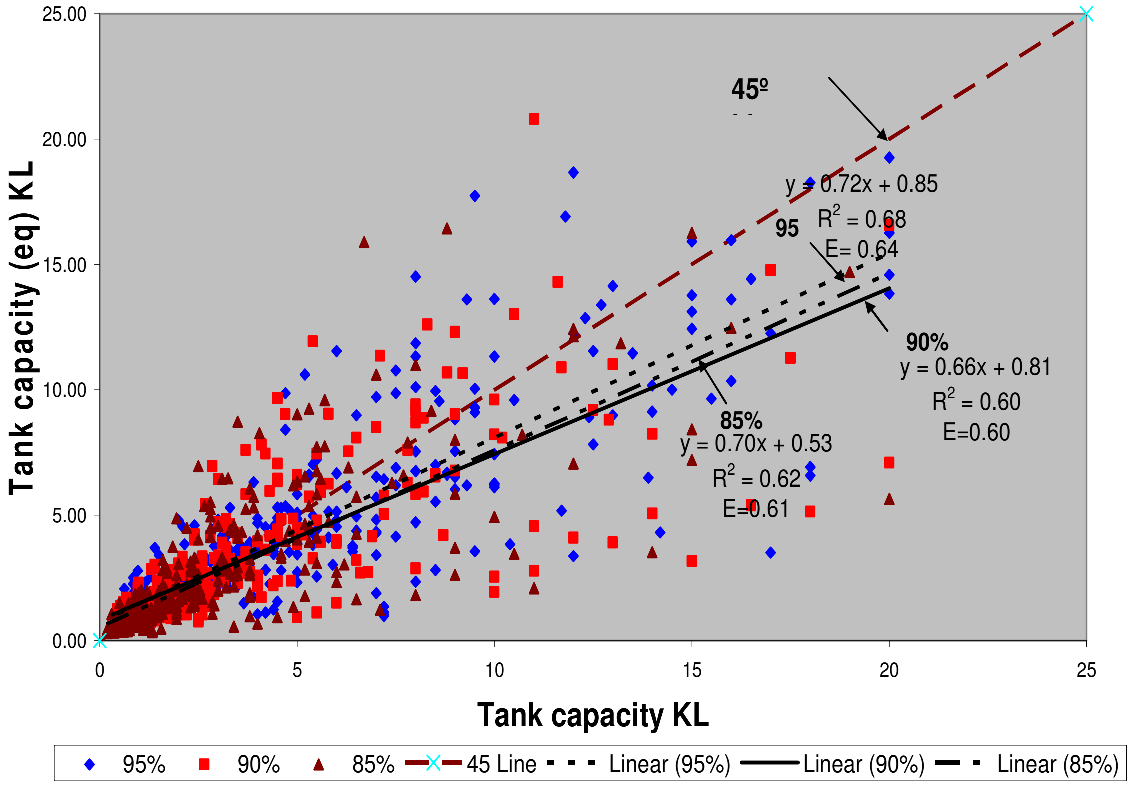

Figure 4.6 Comparison between the tank sizes calculated from the regression equation and the water balance model

Table 4.4 Regression equations and goodness-of-fit parameters between tank sizes calculated from the water balance equation and generalized curve (dependent stations for 95% reliability)

Dependent Station	Equation	R^2	E
Altona	Y=0.72X+0.56	0.80	0.80
Arthur Creek	Y=0.94X+0.05	0.82	0.82
Berwick	Y=0.96X+0.18	0.70	0.60
Caulfield	Y=0.49X +4.10	0.70	0.63
Caulfield North	Y= 0.97X+0.01	0.81	0.78
Cranbourne	Y= 0.96X+0.04	0.84	0.83

Doncaster	Y= 0.76X+0.16	0.82	0.81
Eastern golf club	Y= 0.90X+0.13	0.92	0.88
Hampton	Y=0.98X+0.50	0.90	0.89
Kinglake	Y= 0.85X +0.30	0.88	0.85
Notting Hill	Y=0.96X+0.08	0.82	0.80
Rockbank	Y=0.82X+0.78	0.88	0.85
Sandringham	Y= 0.81X+0.64	0.94	0.92
St Albans	Y=0.87X+0.40	0.93	0.87
Sunshine	Y=0.84X+0.57	0.90	0.80
Werribee	Y=0.58X+1.30	0.90	0.55

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model)*

Table 4.5 Regression equations and goodness of fit parameters between tank sizes calculated from the water balance equation and generalized curve (dependent stations for 90% reliability)

Dependent Station	**Equation**	**R^2**	**E**
Altona	Y=0.86X+0.14	0.96	0.93
Arthur Creek	Y=0.87X+0.27	0.85	0.83
Berwick	Y=1.02X- 0.07	0.81	0.76
Caulfield	Y=0.49X +0.32	0.93	0.85
Caulfield North	Y=1.01X -0.07	0.80	0.75
Cranbourne	Y=1.16X-0.32	0.93	0.93
Doncaster	Y=0.88X+ 0.20	0.96	0.83

Eastern golf club	Y=1.10X -0.13	0.92	0.89
Hampton	Y=1.06X+0.20	0.88	0.88
Kinglake	Y=0.99X+0.01	0.89	0.80
Notting Hill	Y=0.95X+0.10	0.82	0.81
Rockbank	Y=0.88X+0.31	0.95	0.92
Sandringham	Y=0.92X+0.17	0.92	0.91
St Albans	Y=0.88X+0.27	0.95	0.83
Sunshine	Y=0.87X+0.28	0.93	0.92
Werribee	Y=0.53X+0.95	0.94	0.68

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model)*

Table 4.6 Regression equations and goodness of fit parameters between tank sizes calculated from the water balance equation and generalized curve (dependent stations for 85% reliability)

Dependent Station	**Equation**	**R^2**	**E**
Altona	Y=0.89X+0.10	0.96	0.94
Arthur Creek	Y=0.93X+0.06	0.90	0.87
Berwick	Y= 1.17X – 0.36	0.86	0.74
Caulfield	Y=0.35X +0.41	0.87	0.84
Caulfield North	Y=1.25X- 0.30	0.86	0.80
Cranbourne	Y=1.36X -0.42	0.90	0.85
Doncaster	Y =1.21X – 0.22	0.95	0.94
Eastern golf club	Y= 1.25X-0.29	0.85	0.83

Hampton	Y=1.95X+0.09	0.80	0.71
Kinglake	Y= 1.12X+0.24	0.79	0.77
Notting Hill	Y=0.98X+0.05	0.85	0.83
Rockbank	Y=0.91X+0.10	0.91	0.85
Sandringham	Y=1.11X-0.16	0.91	0.77
St Albans	Y=0.86X+0.22	0.95	0.94
Sunshine	Y=0.77X+0.47	0.94	0.91
Werribee	Y=0.54X+0.67	0.92	0.47

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model)*

The R^2 and E values (Figure 4.6) are around 60% when the tank capacities calculated with the developed equation is compared with the values for the water balance equation. However, when this equation is applied to data from individual stations R^2 and E values improve considerably. When the generalized curve equation was applied to data from Werribee the E values with all 3 reliabilities were low. This is mainly due to the large tank sizes obtained from the water balance model in the very low rainfall Werribee area (MAR = 450mm). As a result, when the generalized curve was used to calculate the tank sizes from the whole data set and compared with the tank sizes from the water balance equation, the R^2 and E values are lower than from individual stations.

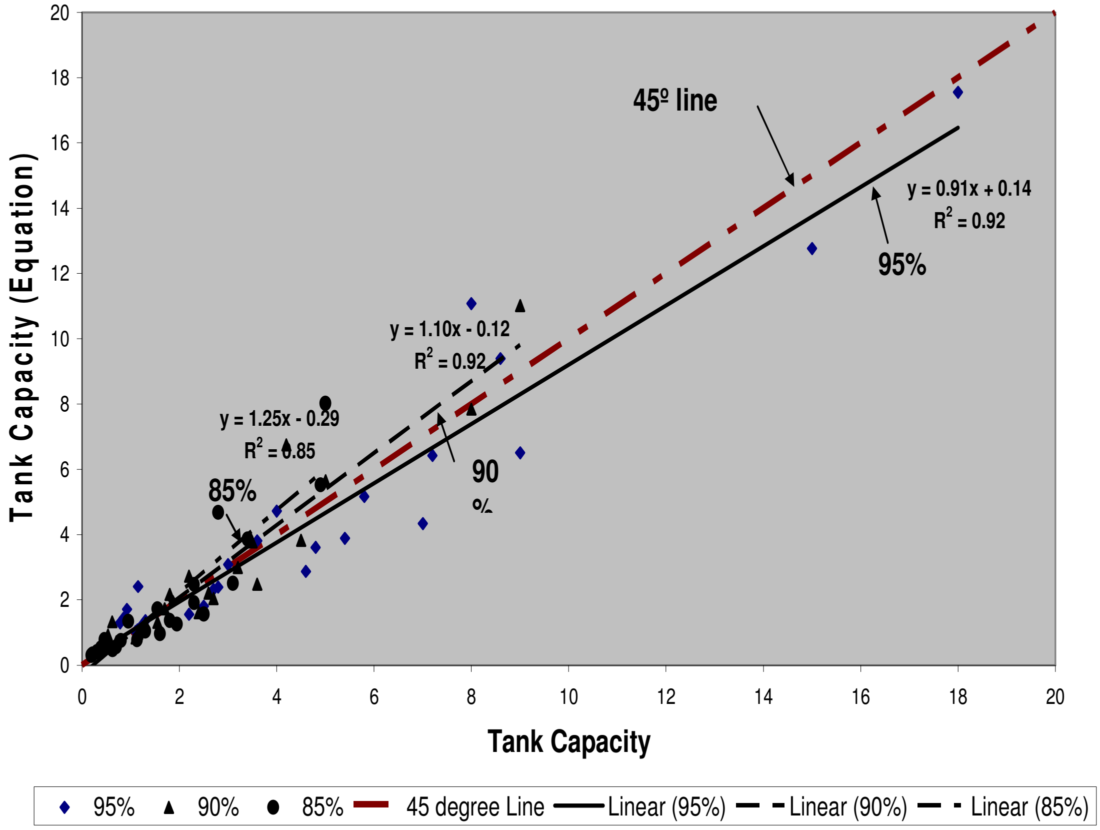

Figure 4.7 Comparison between the tank sizes calculated from the Generalized curve and the water balance model for Eastern Golf Club (Dependent station)

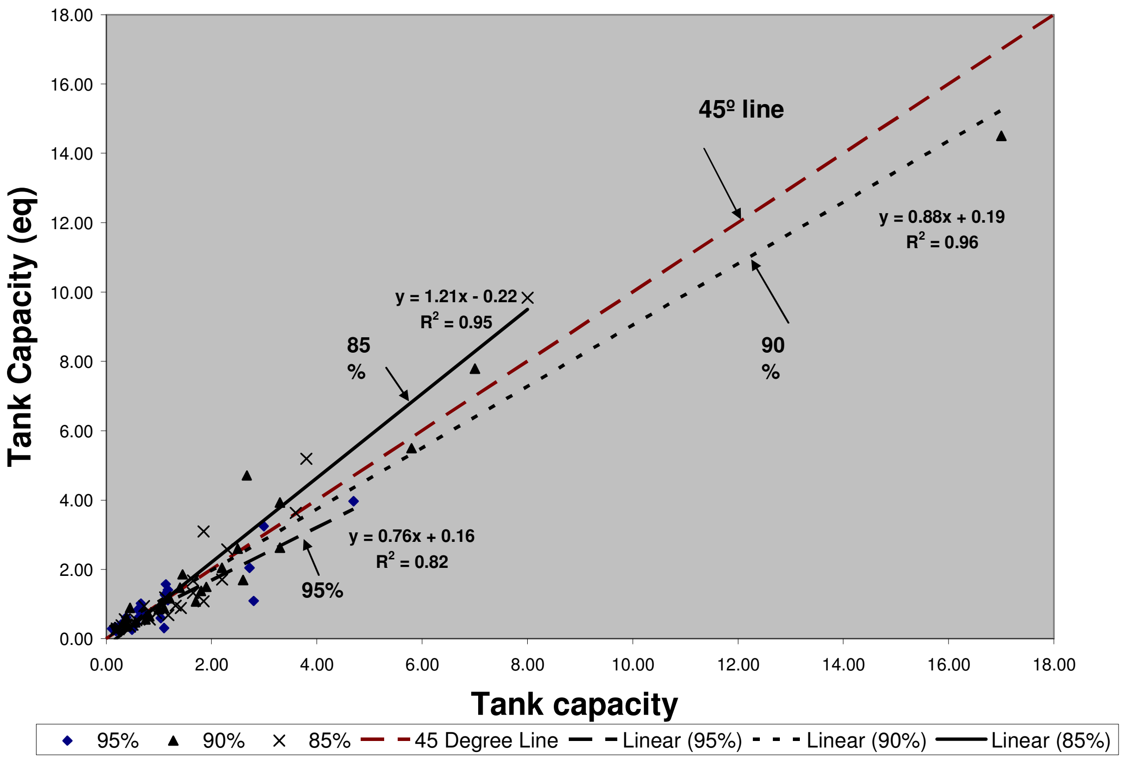

Figure 4.8 Comparison between the tank sizes calculated from the Generalized curve and the water balance model for East Doncaster (Dependent station)

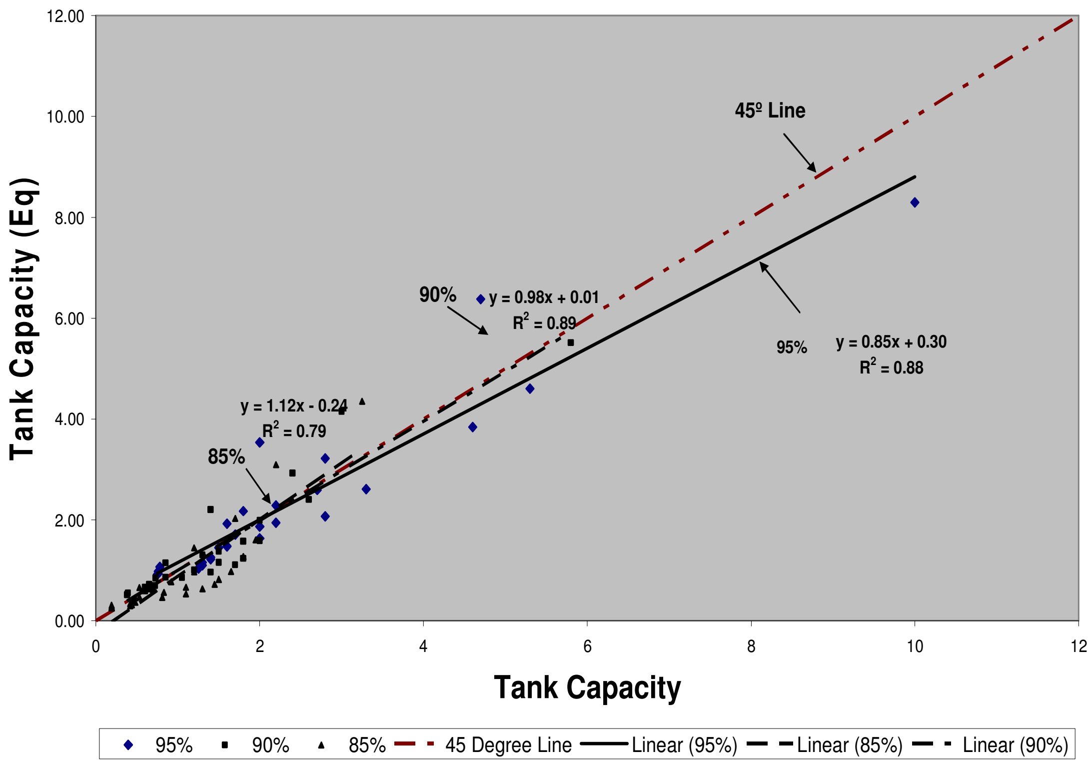

Figure 4.9 Comparison between the tank sizes calculated from the Generalized curve and the water balance model for Kinglake (Dependent station)

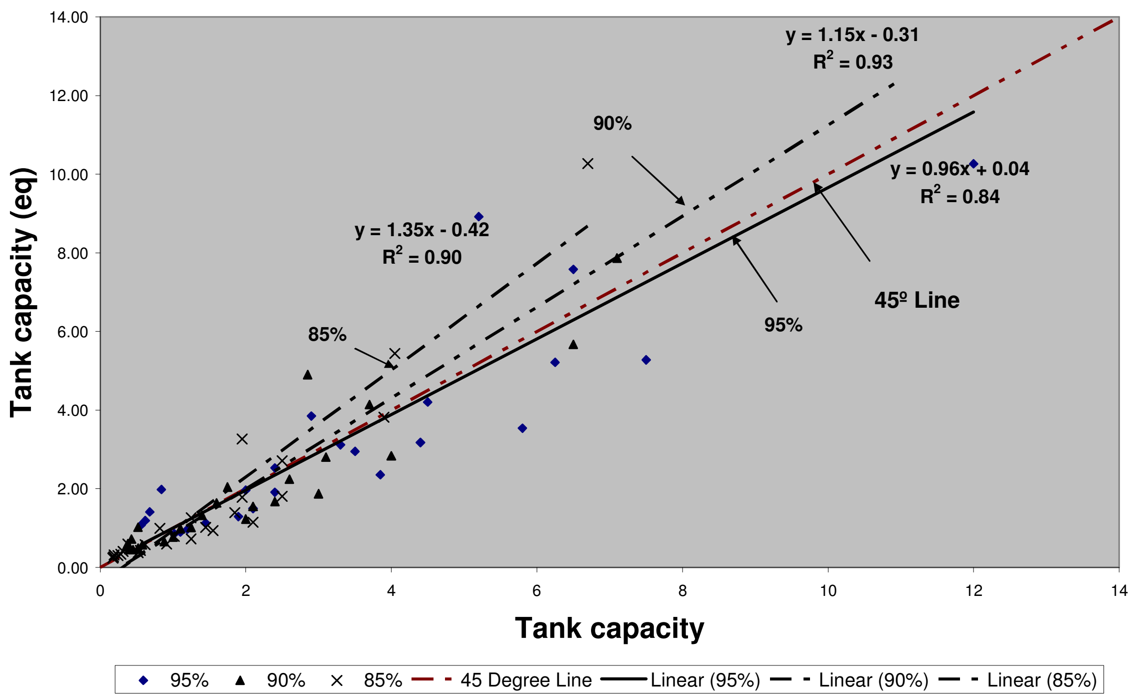

Figure 4.10 Comparison between the tank sizes calculated from the Generalized curve and the water balance model for Cranbourne (Dependent station)

The developed generalized curves (95%, 90% and 85% reliability) were applied to calculate the tank sizes to the data obtained from the stations that were not used to develop the curves (independent stations) to test accuracy. These tank sizes were compared with the tank sizes obtained from the water balance model. The goodness-of-fit parameters are depicted in Tables 4.7, 4.8 and 4.9 and Figures 4.11 to 4.14. The R^2 and E values obtained from all the four stations are above 70% and are considered good. As a result, these curves could be used with confidence in calculating optimum rainwater tank size depending on demand, roof area and MAR. Equations 4.23, 4.24 and 4.25 give the final generalized curve for 95%, 90% and 85% reliabilities.

95% reliability: $$\frac{C}{A^{1.5}} = \left(0.29 * 10^{-3}\right)e^{4.73\frac{D}{AR}} \quad (4.23)$$

90% reliability: $$\frac{C}{A^{1.5}} = \left(0.15 * 10^{-3}\right)e^{5.16\frac{D}{AR}} \quad (4.24)$$

85% reliability: $$\frac{C}{A^{1.5}} = \left(0.08 * 10^{-3}\right)e^{5.58\frac{D}{AR}} \quad (4.25)$$

Table 4.7 Regression equations and goodness of fit parameters between tank sizes calculated from the water balance equation and generalized curve (individual independent stations for 95% reliability)

Independent Station	Equation	R^2	E
Kew	Y=0.89X+0.26	0.89	0.89
Mitcham	Y= 0.91X+0.14	0.84	0.83
Mountview	Y=1.10X-0.42	0.92	0.86
Surrey Hills	Y= 0.73X +1.17	0.91	0.87

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model)*

Table 4.8 Regression equations and goodness of fit parameters between tank sizes calculated from the water balance equation and generalized curve (individual independent stations for 90% reliability)

Independent Station	Equation	R^2	E

Kew	Y = 0.97X+0.05	0.93	0.93
Mitcham	Y=1.05X -0.11	0.94	0.92
Mountview	Y=1.16X-0.38	0.87	0.78
Surrey Hills	Y=0.82X+0.52	0.93	0.91

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model)*

Table 4.9 Regression equations and goodness of fit parameters between tank sizes calculated from the water balance equation and generalized curve (individual independent stations for 85% reliability)

Independent Station	Equation	R^2	E
Kew	Y=1.21X-0.26	0.90	0.90
Mitcham	Y=0.97X-0.14	0.84	0.82
Mountview	Y=1.24X-0.32	0.86	0.73
Surrey Hills	Y=0.61X+0.71	0.88	0.80

*** Y = Tank Capacity (Generalized Curve); X = Tank Capacity (Water Balance Model*

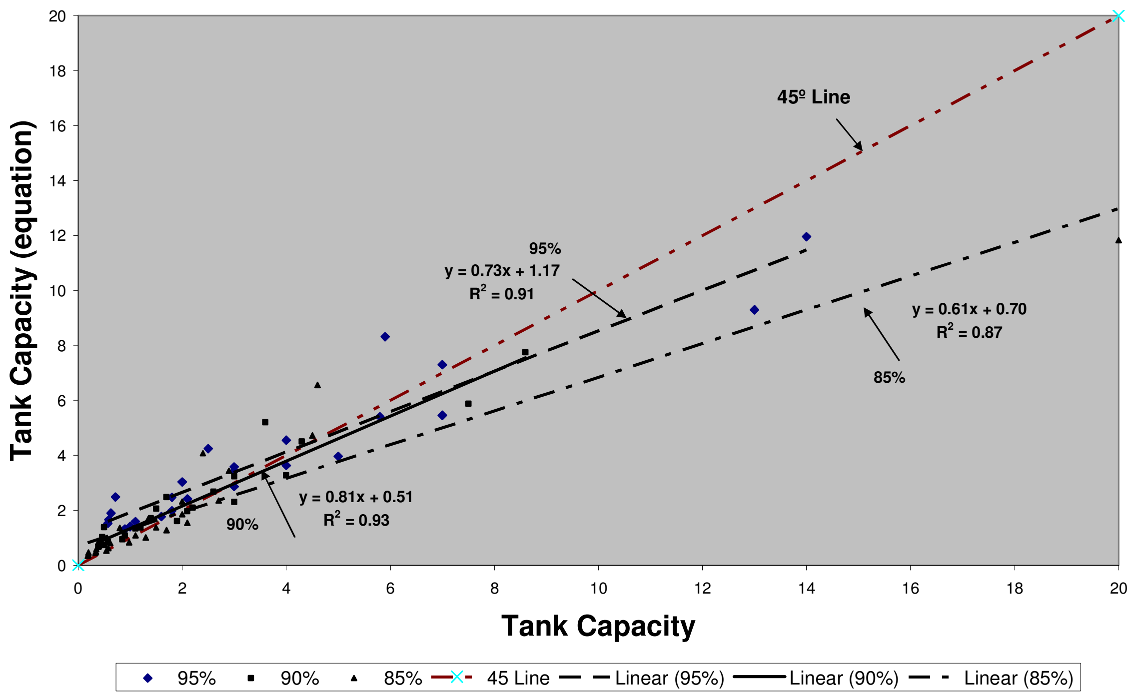

Figure 4.11 Comparison between the tank sizes calculated from generalized curve and the water balance model for Surrey Hills (Independent Station)

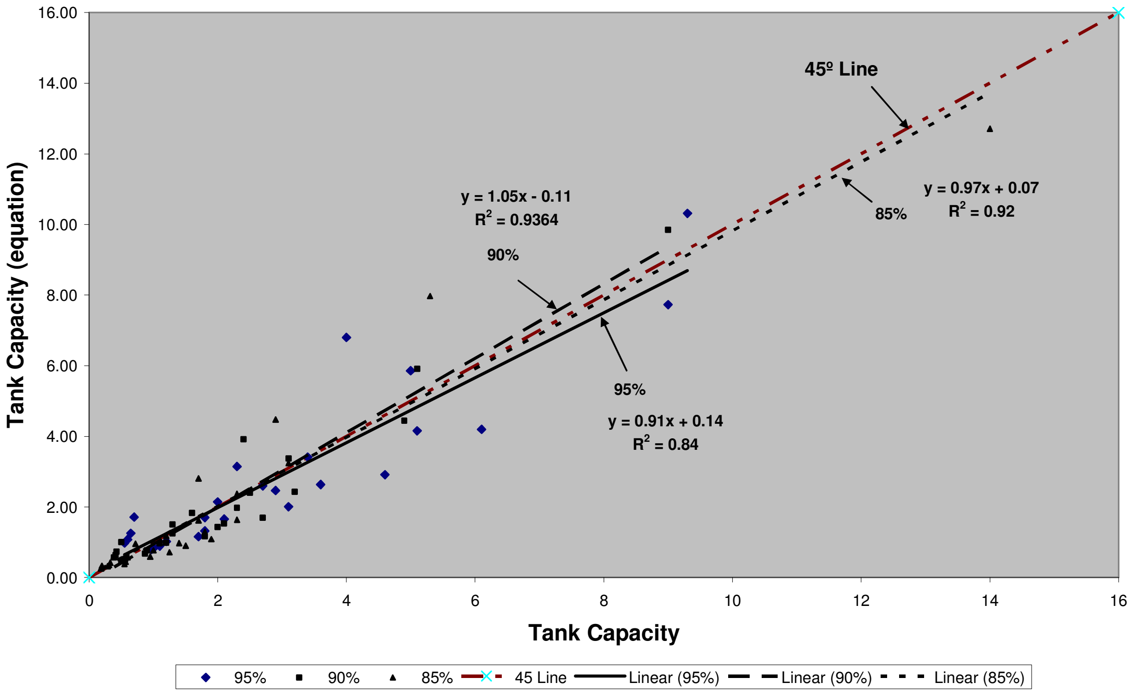

Figure 4.12 Comparison between the tank sizes calculated from generalized curve and the water balance model for Mitcham (Independent Station)

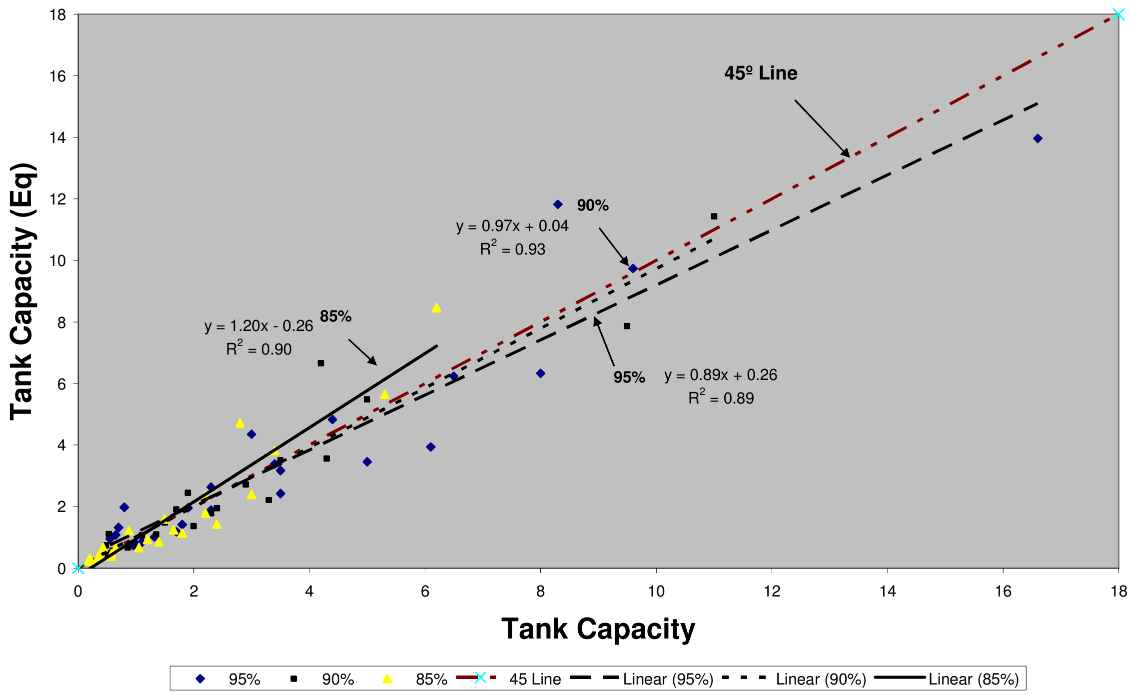

Figure 4.13 Comparison between the tank sizes calculated from the generalized curve and the water balance model for Kew (Independent Station)

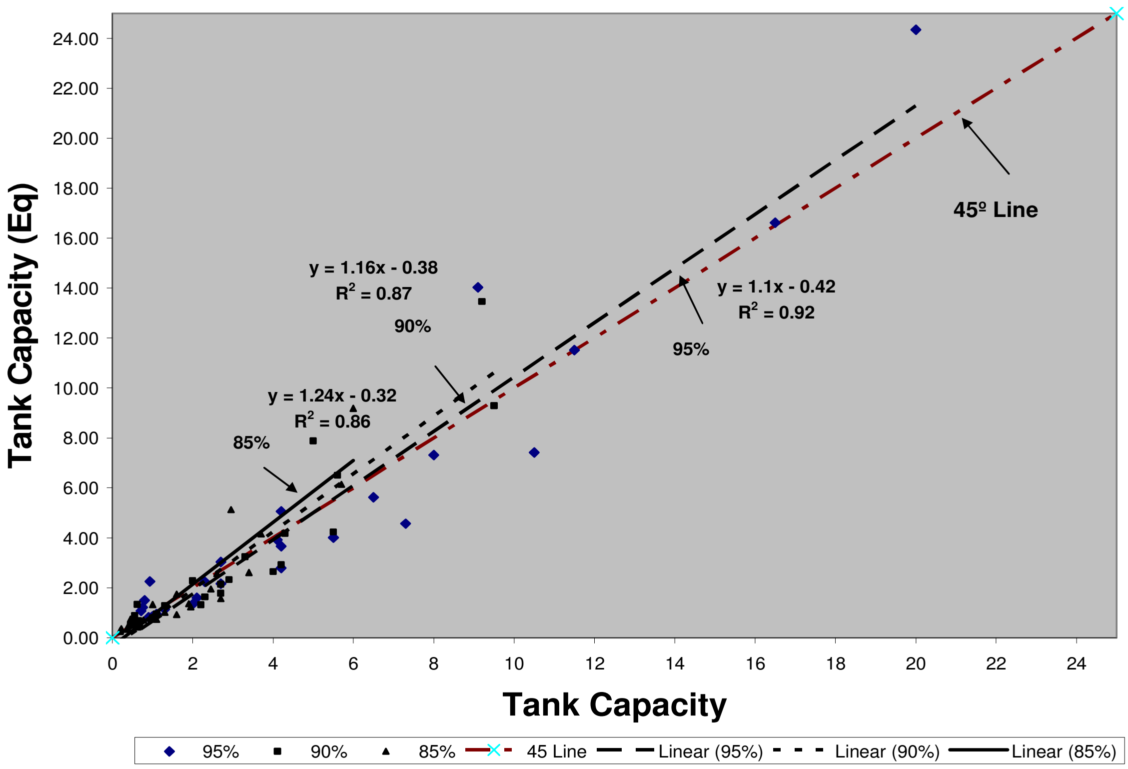

Figure 4.14 Comparison between the tank sizes calculated from the generalized curve and the water balance model for Mountview (Independent Station)

It was decided to investigate the relationship between two dimensionless numbers for different roof areas, demand and MAR values separately. The roof area was varied between $100m^2$ – $250m^2$; rainfall was varied between 450 mm to 1050 mm and demand was varied from garden watering to toilet; garden and laundry use. In Figure 4.15, the roof areas were fixed at $100m^2$, $150m^2$, $200m^2$ and $250m^2$. The tank capacity was obtained from the water balance model with 85% supply reliability. From the above Figure it is evident that best fit lines for all roof areas meet when π_2 (D/AR) is about 0.7. This states that the dimensionless parameter π_1 ($C/A^{1.5}$) does not depend on roof area if D/AR is about 0.7. However, D and MAR will vary accordingly to obtain a π_2 of 0.7.

For other π_2 (D/AR) values the π_1 ($C/A^{1.5}$) deviates from the value obtained from the generalized curve. Figures B13 and B14 in Appendix B depict the π_1 and π_2 relationships for 90% and 85% reliabilities. Similar to Figure 4.15, for 90% and 95% reliabilities the π_1 does not vary with the roof area when π_2 is approximately 0.8. It is also noted that for a particular π_2 value, if the roof area is between $150m^2$ to $200m^2$, the deviation from the generalized curve is small for all reliabilities.

Figure 4.16 delineates the π_1 and π_2 relationships for fixed MAR values whilst changing the roof areas and demand values for 85% supply reliability curves due to variation of rainfall. Figure 4.16 illustrates that π_1 decreases when mean annual rainfall increases. Similar results were obtained for 90% and 95% reliabilities which are shown in Appendix B (Figures B15 and B16).

Figure 4.17 depicts the relationship between π_1 and π_2 for 85% reliability curves for a particular demand type. The curves show that for a constant π_2 value, π_1 varies with demand. There is a distinct difference between the curve for garden watering and the remaining curves.

In addition, all the curves for the demands related to laundry (L, G+L, T+G+L and T+L) are almost parallel and higher tank capacities for a constant π_2 value are required to meet the high demand for laundry use. The curves for 90% and 95% reliabilities are depicted in Appendix B, Figures B17 and B18.

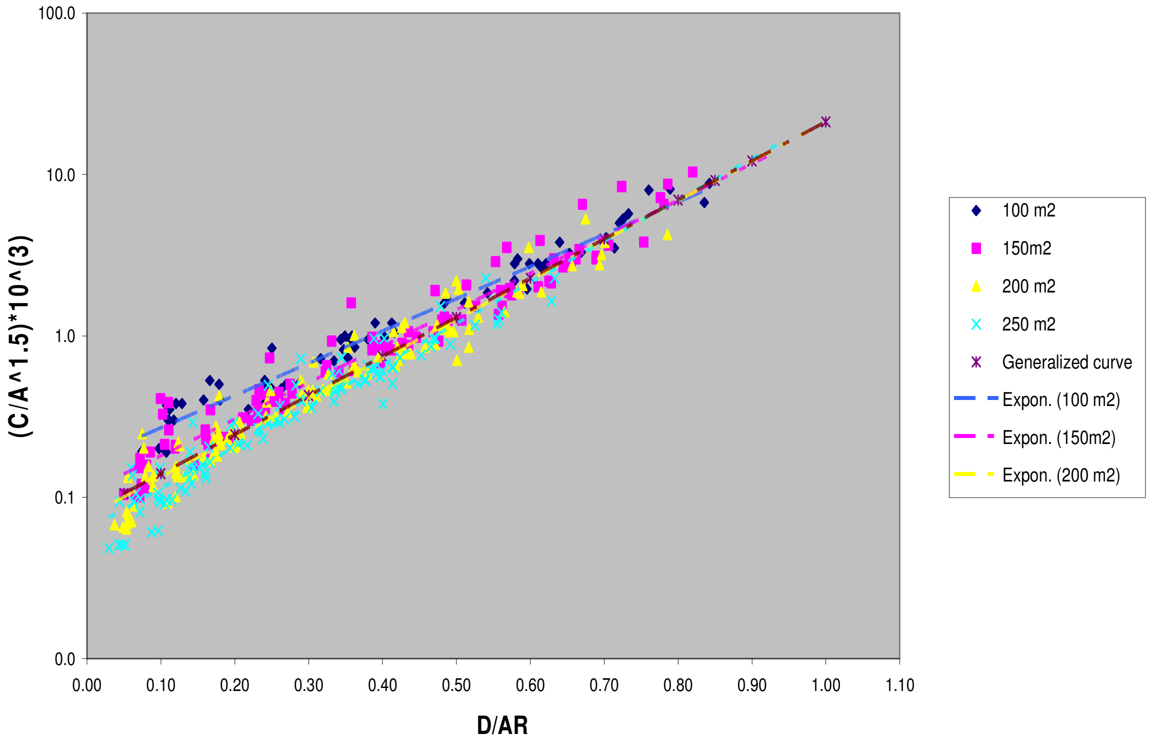

Figure 4.15 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different roof areas (85% reliability)

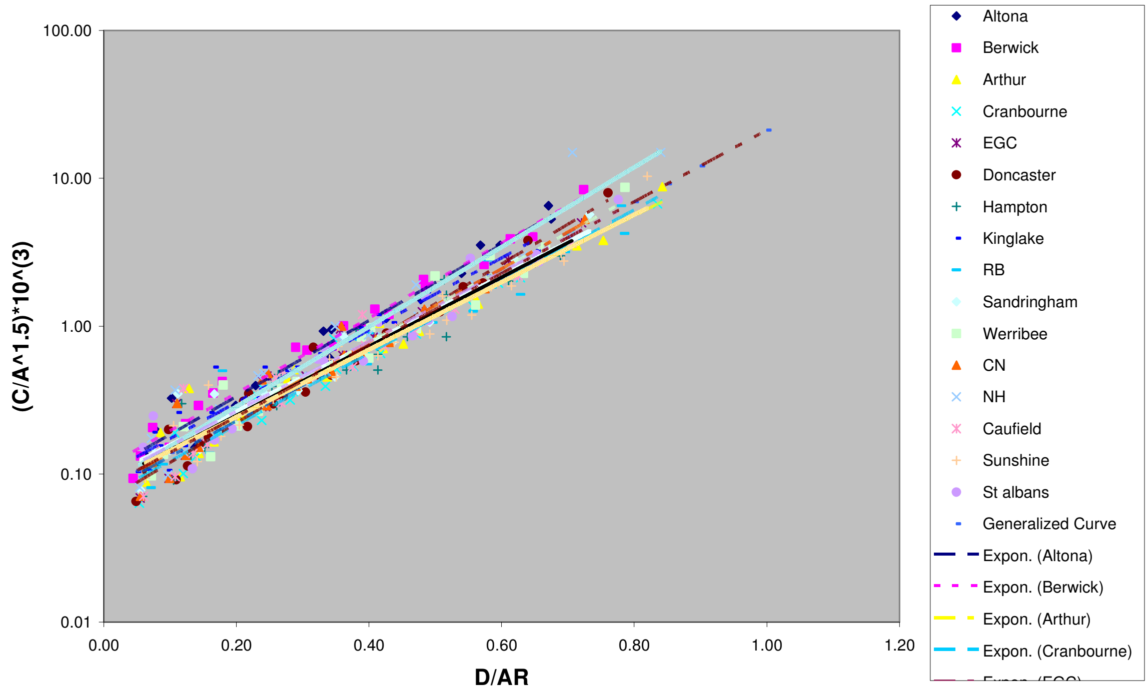

Figure 4.16 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different rainfall (85% reliability)

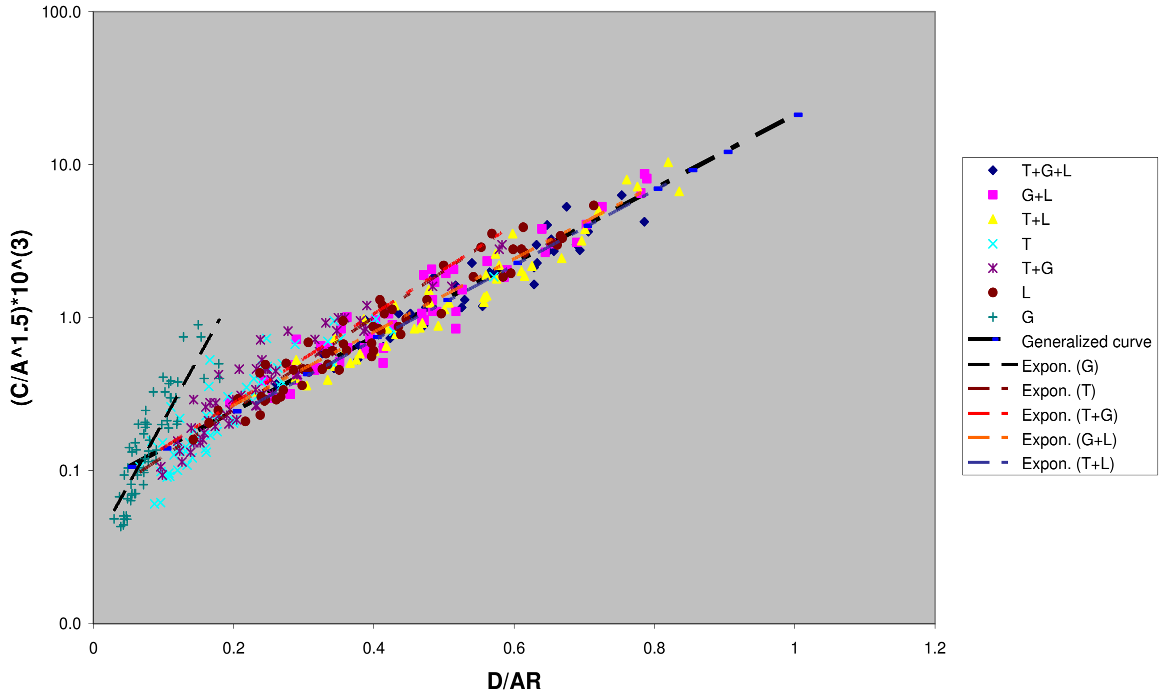

Figure 4.17 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different demand (85% reliability)

Figures 4.18, 4.19 and 4.20 delineate the range of tank sizes when roof area was changed from 100 m^2 to 250 m^2 at different rainfall stations for 95%, 90% and 85%

reliabilities respectively when the demand is limited to toilet use only. As expected, tank sizes increase with the reliability. In the above stated Figures the rainfall stations are shown in the ascending order of MAR. It is evident from the above Figures that there are 3 distinct ranges for tank sizes based on MAR. The three ranges are:

- MAR less than 550mm (Werribee, Altona, Rockbank, Sunshine and St. Albans)
- MAR of between 550mm and 850mm (Arthurs Creek, Caulfield, Hampton, Kew, Sandringham, Mountview, Berwick Caulfield North, Surrey Hills, Notting Hills, Eastern Golf Club, East Doncaster, Cranbourne and Mitcham)
- MAR of above 850mm (Kinglake)

Figures 4.21 to 4.26 depict the range of tank sizes obtained for different types of demands from different stations for 85% reliability. Similar information for 90% and 95% reliabilities are given in Appendix C (Figures C 1 to C 12).

The Figures 4.20, 4.21 and 4.22 depict the rainwater tank sizes for toilet flushing, garden watering and laundry use respectively. The tank sizes in Figures 4.23 to 4.26 are for laundry demand together with garden and/or toilet demand. As mentioned earlier, it is evident that there are distinct ranges for rainwater tanks for the region with MAR of less than 550mm and above 850mm. Low rainfall areas need very big tanks if water is being used in the laundry. On the other hand, for the high rainfall areas (Kinglake) where rainfall is greater than 850mm, a 5kL tank can fulfil any demand whilst maximizing supply reliability. Tables 4.10 to 4.16 depict the range of rainwater tanks for different reliabilities and specific demand types by interpreting the results from the Figures (4.18 to 4.26 and Appendix C). In Tables 4.13, 4.14 and 4.16 are when the rainwater is used for garden and toilet; laundry and toilet; and garden, toilet and laundry respectively. As depicted in above tables, the upper limits of tank sizes are very big. It should be noted that in all above 3 tables the rainwater is being used in the laundry (maximum annual use) and the minimum reliability (deemed acceptable) is 85%. As such, even if the annual rainfall is within the average range in Melbourne, rainwater only will not be able to provide an acceptable reliability. So, a potential customer of a rainwater tank can select the tank size based on reliability by using the above stated table. The above stated range is applicable for the rainfall stations in areas with average annual rainfall between 550mm to 800mm.

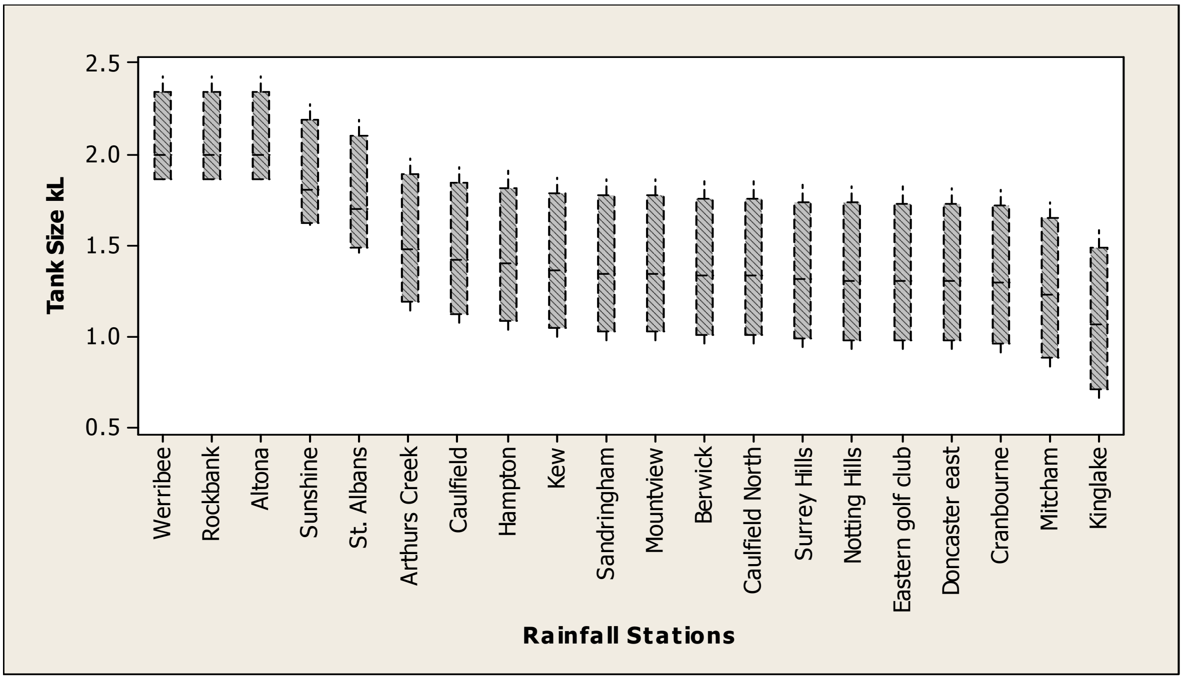

Figure 4.18 Variation in tank sizes from roof areas at different Locations across Melbourne for 95% reliability and toilet use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

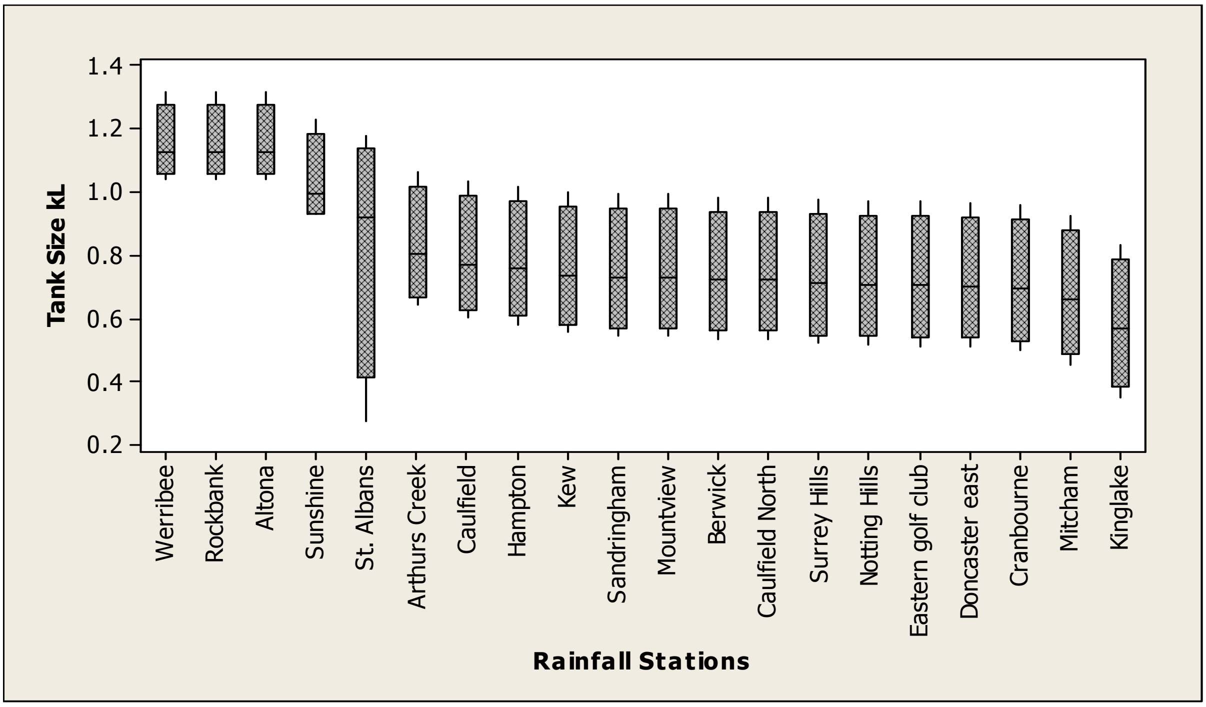

Figure 4.19 Variation in tank sizes from roof areas at different Locations across Melbourne for 90% reliability and for toilet use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

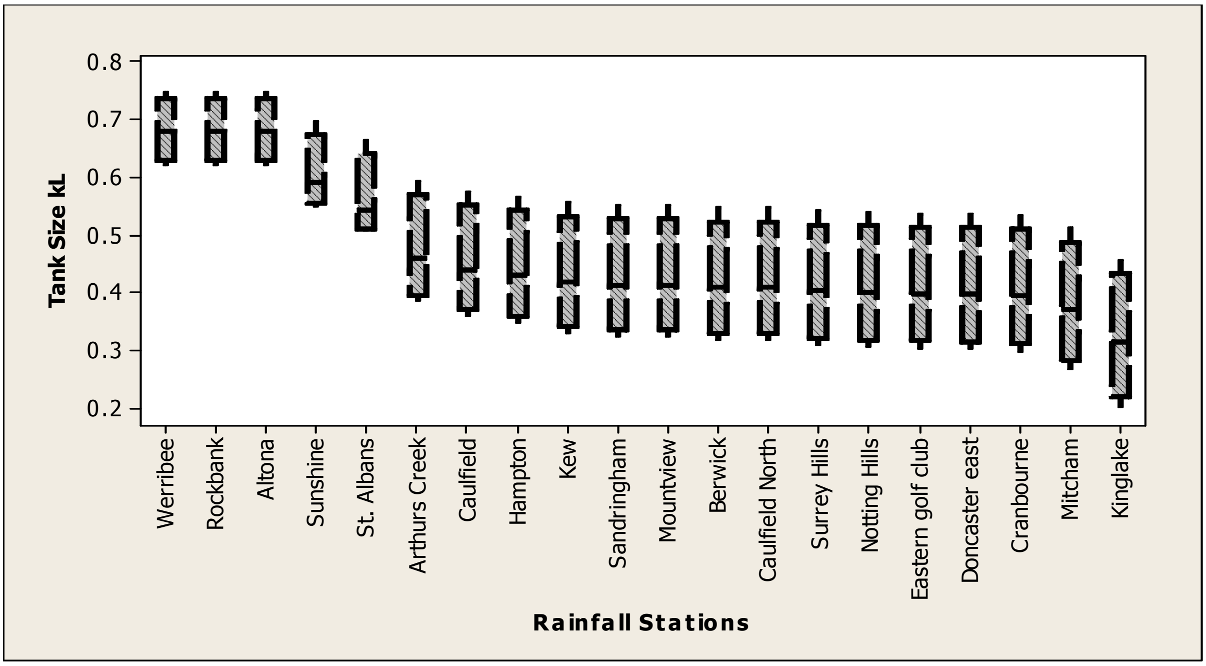

Figure 4.20 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for toilet use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2

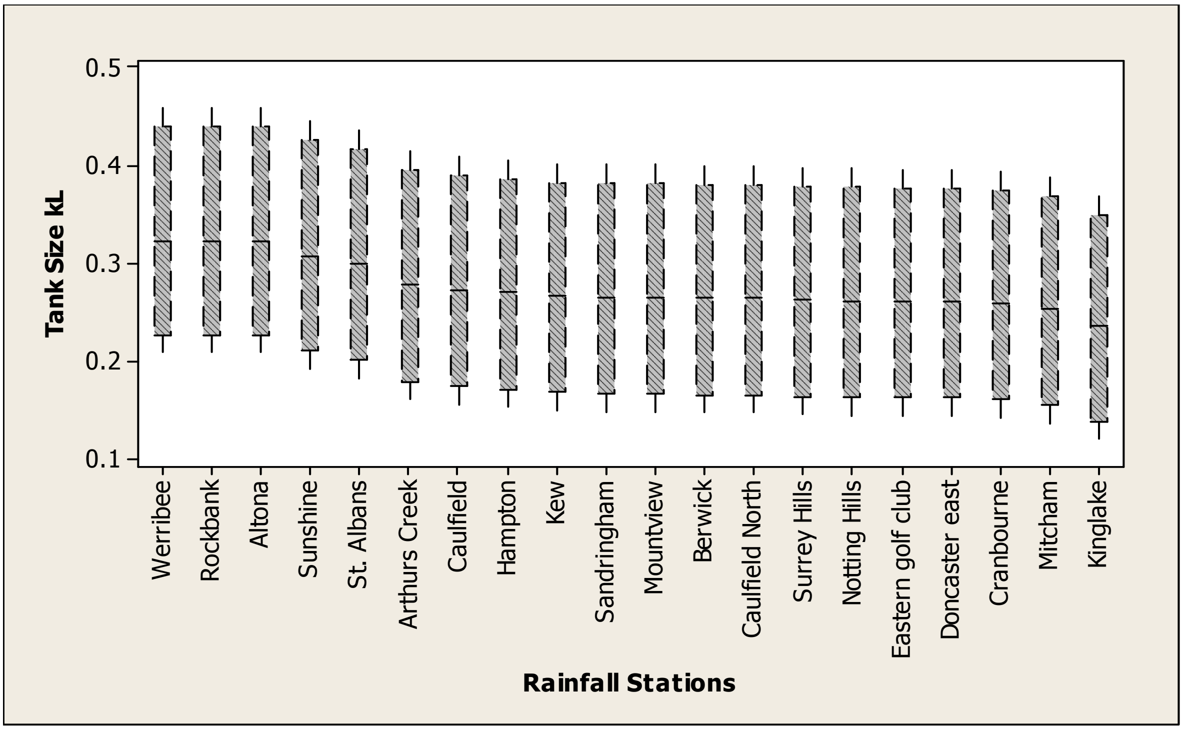

Figure 4.21 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for garden use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

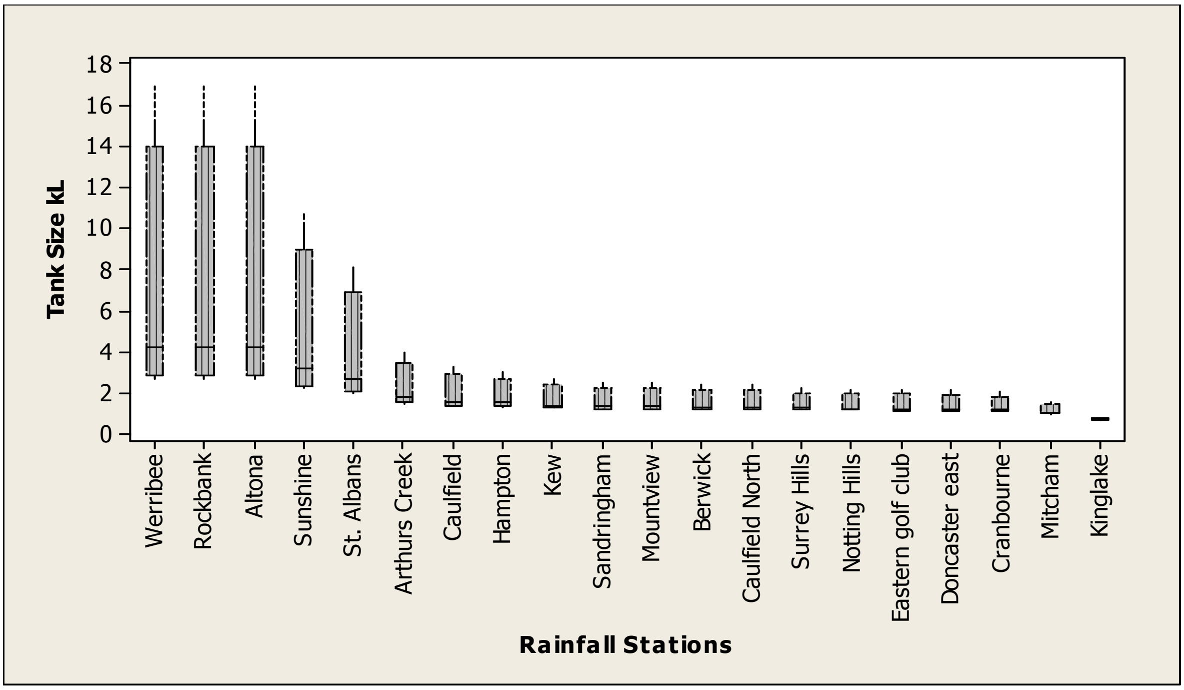

Figure 4.22 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for laundry use (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

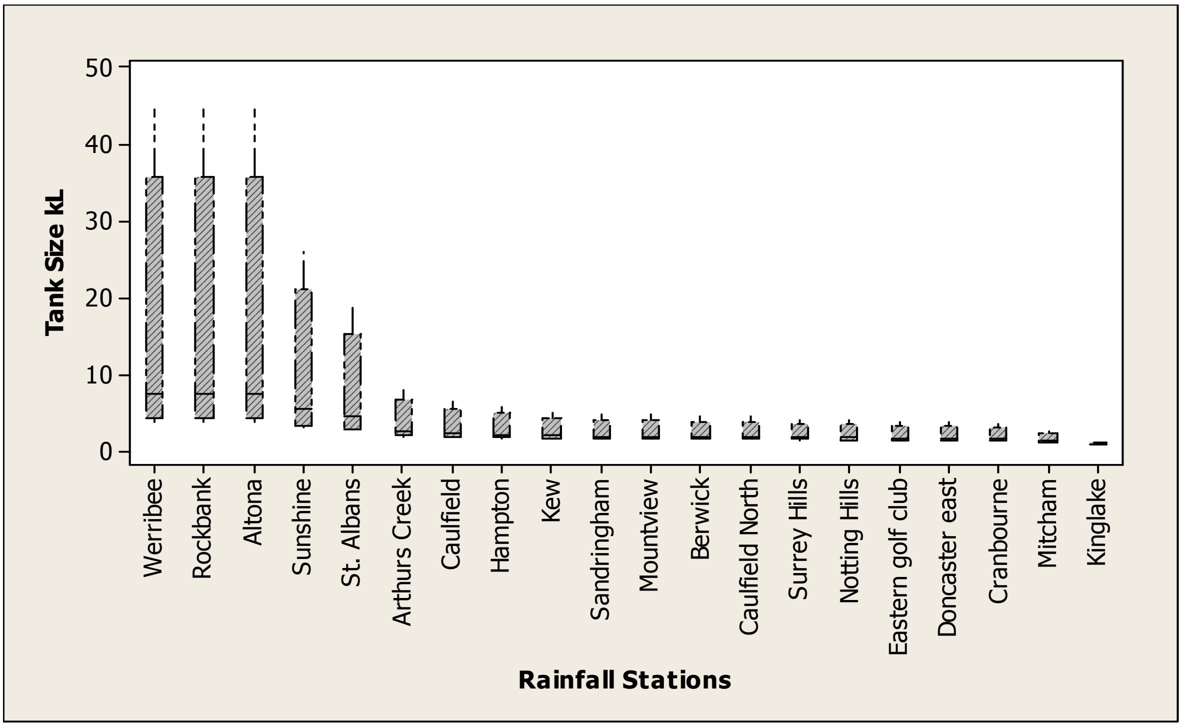

Figure 4.23 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for garden and laundry use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

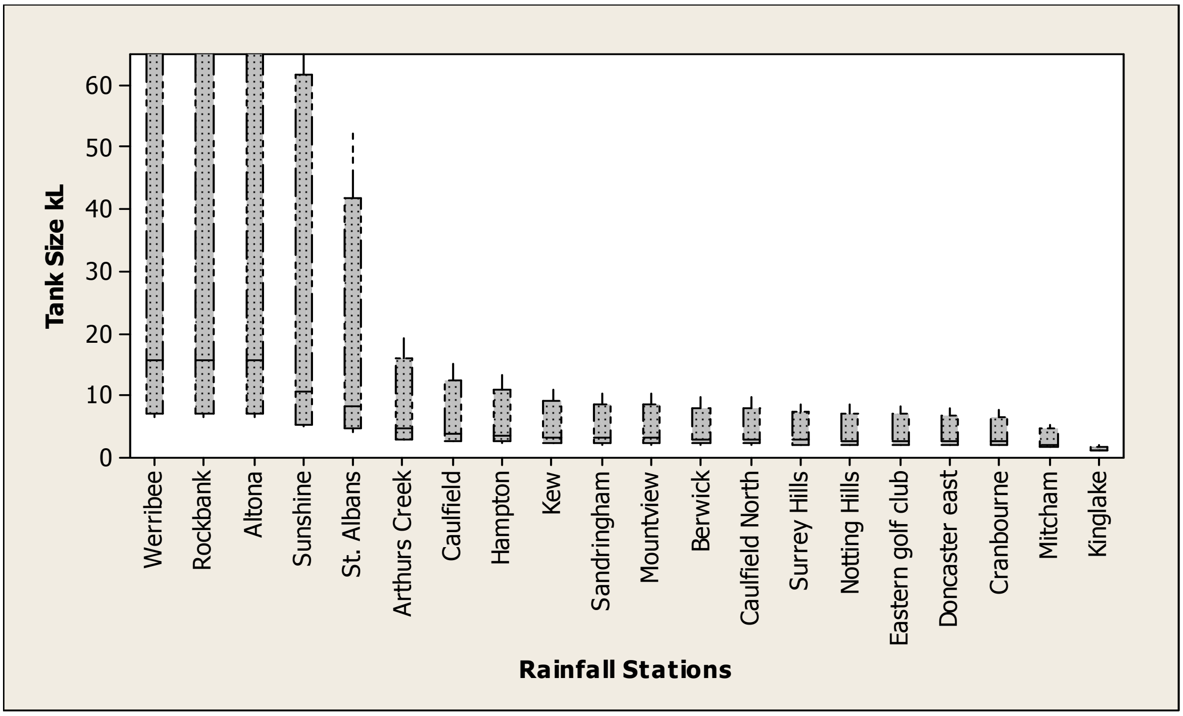

Figure 4.24 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for toilet and laundry use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

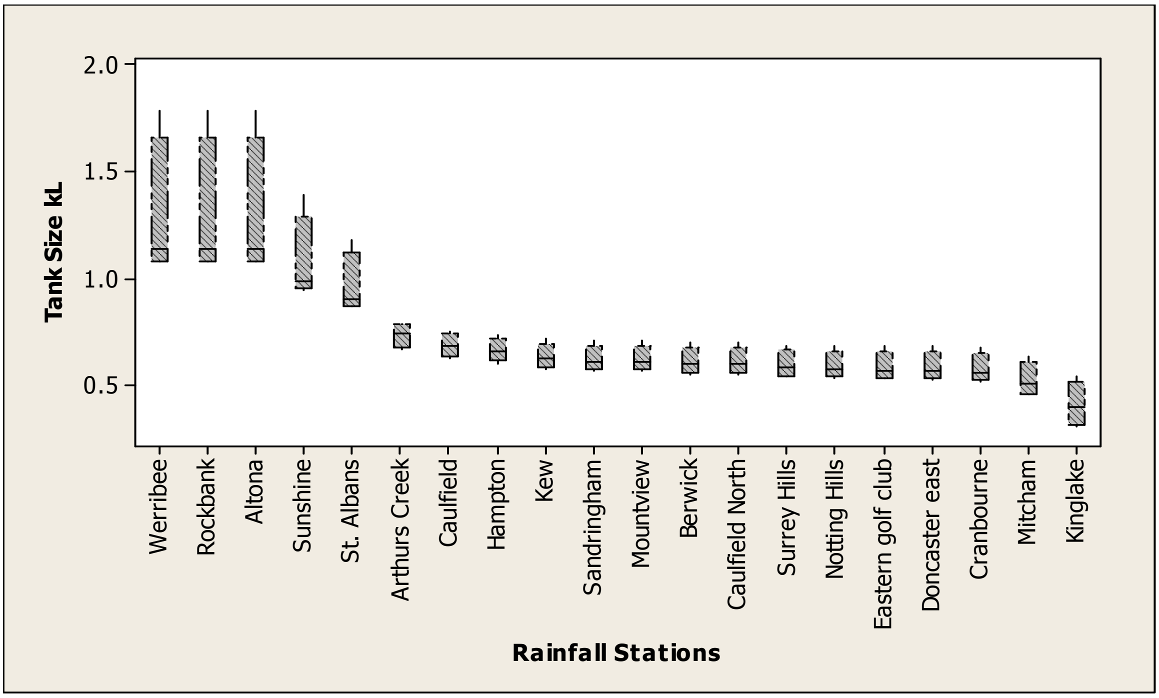

Figure 4.25 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and for toilet and garden use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

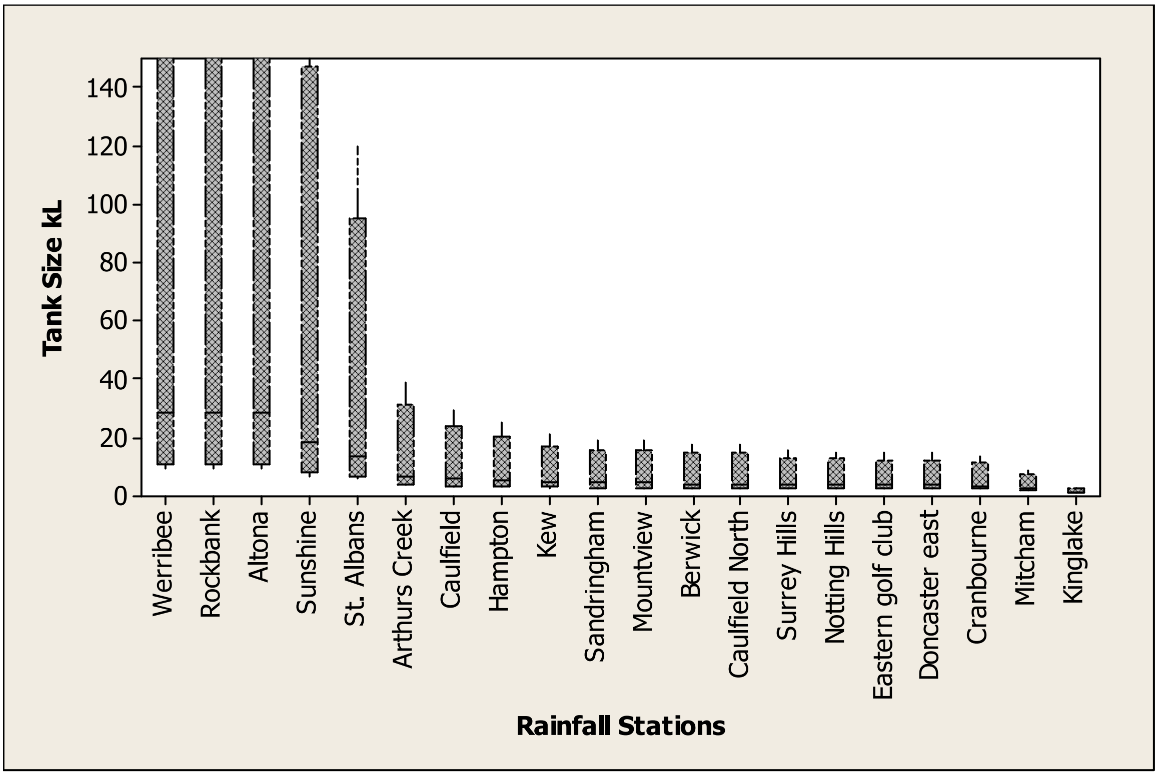

Figure 4.26 Variation in tank sizes from roof areas at different Locations across Melbourne for 85% reliability and Toilet, Garden and Laundry use. (Lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

Table 4.10 Range of tank sizes for toilet use if MAR is between 550mm and 850mm when roof areas vary from 100m^2 to 250m^2.

Reliability	**Range of tank size (kL)**
95%	0.8-2.0
90%	0.5-1.1
85%	0.2-0.6

Table 4.11 Range of tank sizes for garden use if MAR is between 550mm and 850mm when roof areas vary from 100m^2 to 250m^2.

Reliability	**Range of tank size (kL)**
95%	0.5-1.5
90%	0.2-0.8
85%	0.1-0.4

Table 4.12 Range of tank sizes for laundry use if MAR is between 550mm and 850mm when roof areas vary from $100m^2$ to $250m^2$.

Reliability	**Range of tank size (kL)**
95%	3.6-8.7
90%	2.0-5.6
85%	1.2-4.0

Table 4.13 Range of tank sizes for garden and laundry use if MAR is between 550mm and 850mm when roof areas vary from $100m^2$ to $250m^2$.

Reliability	**Range of tank size (kL)**
95%	4.5-16.0
90%	2.5-10.5
85%	1.5-8.0

Table 4.14 Range of tank sizes for toilet and laundry use if MAR is between 550mm and 850mm when roof areas vary from $100m^2$ to $250m^2$.

Reliability	**Range of tank size (kL)**
95%	5.6-34.0
90%	3.2-24.0
85%	2.0-19.0

Table 4.15 Range of tank sizes for toilet and garden use if MAR is between 550mm and 850mm when roof areas vary from $100m^2$ to $250m^2$.

Reliability	**Range of tank size (kL)**
95%	1.5-2.5
90%	0.9-1.4
85%	0.5-0.8

Table 4.16 Range of tank sizes for toilet, garden and laundry use if MAR is between 550mm and 850mm when roof areas vary from $100m^2$ to $250m^2$.

Reliability	Range of tank size (kL)
95%	7.0-63.0
90%	4.0-46.0
85%	2.5-39.0

From the above Tables 4.10 to 4.16 it can be observed that for low demands (T, G and T+G) the size of the rainwater tank is normally less than 5kL for a single property household in Melbourne although some large tanks are now being used for residential purposes. In addition, it is possible to use rainwater in the laundry with 85% reliability in many parts of Melbourne (550mm<MAR<850mm) by installing a 5kL tank. However, it will not be possible to meet the laundry demand with 90% or 95% reliability from a 5kL tank in a residential property.

To summaries, for a location with low rainfall (less than 550mm), irrespective of roof area available the demand that could be met will be small. In addition, the analysis shows that rainwater cannot be used in the laundry (L, T+L, G+L and T+G+L) with a reasonable level of reliability (above 85%) in all areas around Melbourne except in high rainfall areas (greater than 850mm) such as Kinglake.

4.5 Analysis of the generalized curve

Analysis of the generalized curve can be considered as a useful tool in water balance model building as well as in water balance model evaluation because it can illustrate the model efficacy with a view to showing behaviour response to changes in parameter values. As a result, further analysis can help to build confidence in the model by studying the uncertainties that are often associated with parameters in the model. In this study, it was decided to carry out analysis of the model for different rainfall stations and varied demand. To gain confidence of the developed reliability centred curves, it was decided to obtain percentage error between the tank sizes calculated using the water balance model and the developed generalised curves. The percentage error was calculated by using Equation 4.27.

% error = ($\frac{AV - EV}{AV}$) x 100 (4.27)

where,

EV= estimated value (Value from generalized curve)

AV= actual value (Value from water balance model)

Tables 4.17 to 4.23 depict the % error between the tank sizes calculated from the water balance model and generalized curve for different demand types with a supply reliability of 85%. The percentage error in tank sizes for low rainwater demand (toilet; garden or toilet and garden together) is higher than for high rainwater demand. However, as shown in Tables 4.10 and 4.11, when the intended use of rainwater is low (toilet or garden) the range of tank sizes are small (Figures 4.20 and 4.21) especially if the average rainfall is larger than 550mm/year. As a result, by analysing the results of these tables, it can be concluded that although for low demand the % error between the water balance model and generalized curve for different reliabilities is high, the variation in actual tank sizes is not significant.

Furthermore, the tank sizes calculated from the water balance model are within the recommended range of tank sizes for a particular demand (Tables 4.17 to 4.23).

Table 4.17 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Toilet (250 m^2 roof area)

Rainfall stations	Demand	Tank capacity (kL)		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	T	0.52	0.78	49.4%
620 (Arthur Creek)	T	0.38	0.60	58.2%
710 (Berwick)	T	0.60	0.55	-8.5%
1054 (Kinglake)	T	0.42	0.46	9.1%

Table 4.18 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Garden (250 m^2 roof area)

Rainfall stations	Demand	Tank capacity (kL)	% Error

		Water Balance	Generalized curve	
454 (Werribee)	G	0.39	0.47	22.8%
620 (Arthur Creek)	G	0.25	0.42	68.5%
710 (Berwick)	G	0.31	0.40	9.4%
1054 (Kinglake)	G	0.22	0.37	69.7%

Table 4.19 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and Laundry demand (250 m^2 roof area)

Rainfall stations	Demand	Tank capacity kL		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	L	2.40	2.94	22.6%
620(Arthur Creek)	L	1.20	1.56	29.6%
710(Berwick)	L	1.80	1.24	-31.0%
1054 (Kinglake)	L	0.81	0.79	-2.0%

Table 4.20 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Laundry and garden (250 m^2 roof area)

Rainfall	Demand	Tank capacity (kL)		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	G+L	3.80	4.40	15.7%
620(Arthur Creek)	G+L	1.80	2.07	15.2%
710(Berwick)	G+L	2.55	1.59	-37.6%
1054 (Kinglake)	G+L	1.10	0.94	-14.8%

Table 4.21 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Toilet and Laundry (250 m^2 roof area)

Rainfall	Demand	Tank capacity (kL)		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	T+L	5.50	7.23	31.5%
620(Arthur Creek)	T+L	2.20	2.96	34.4%

710(Berwick)	T+ L	2.90	2.16	-25.6%
1054 (Kinglake)	T+L	1.30	1.15	-11.5%

Table 4.22 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Toilet and Garden (250 m^2 roof area)

Rainfall stations	Demand	Tank capacity (kL)		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	T+G	1.05	1.16	10.6%
620(Arthur Creek)	T+G	0.65	0.80	22.4%
710(Berwick)	T+G	1.15	0.70	-38.9%
1054 (Kinglake)	T+G	0.42	0.54	28.8%

Table 4.23 Comparison in tank sizes between water balance model and generalized curve at different locations for 85% Reliability and a constant demand of Toilet, garden and Laundry (250 m^2 roof area)

Rainfall stations	Demand	Tank capacity (kL)		% Error
		Water Balance	Generalized Curve	
454 (Werribee)	T+G+L	9.00	10.81	20.1%
620(Arthur Creek)	T+G+L	3.00	3.94	31.3%
710(Berwick)	T+G+L	3.80	2.76	-27.4%
1054 (Kinglake)	T+G+L	1.45	1.36	-6.3%

A similar methodology could be adopted to develop generalised curves with dimensionless numbers for other reliabilities. Developed generalized curves can be used effectively to obtain the optimal tank size depending on the user selected demand and reliability. Figure 4.27 depicts the decision making flowchart for selecting the optimum tank size by using generalized curve and selected variables. However, the user needs to appreciate the concept of reliability as there are significant costs related tradeoffs to be made prior to purchasing a rainwater tank. The costs of rainwater tank as well as the other associated costs have been discussed in Chapter 7.

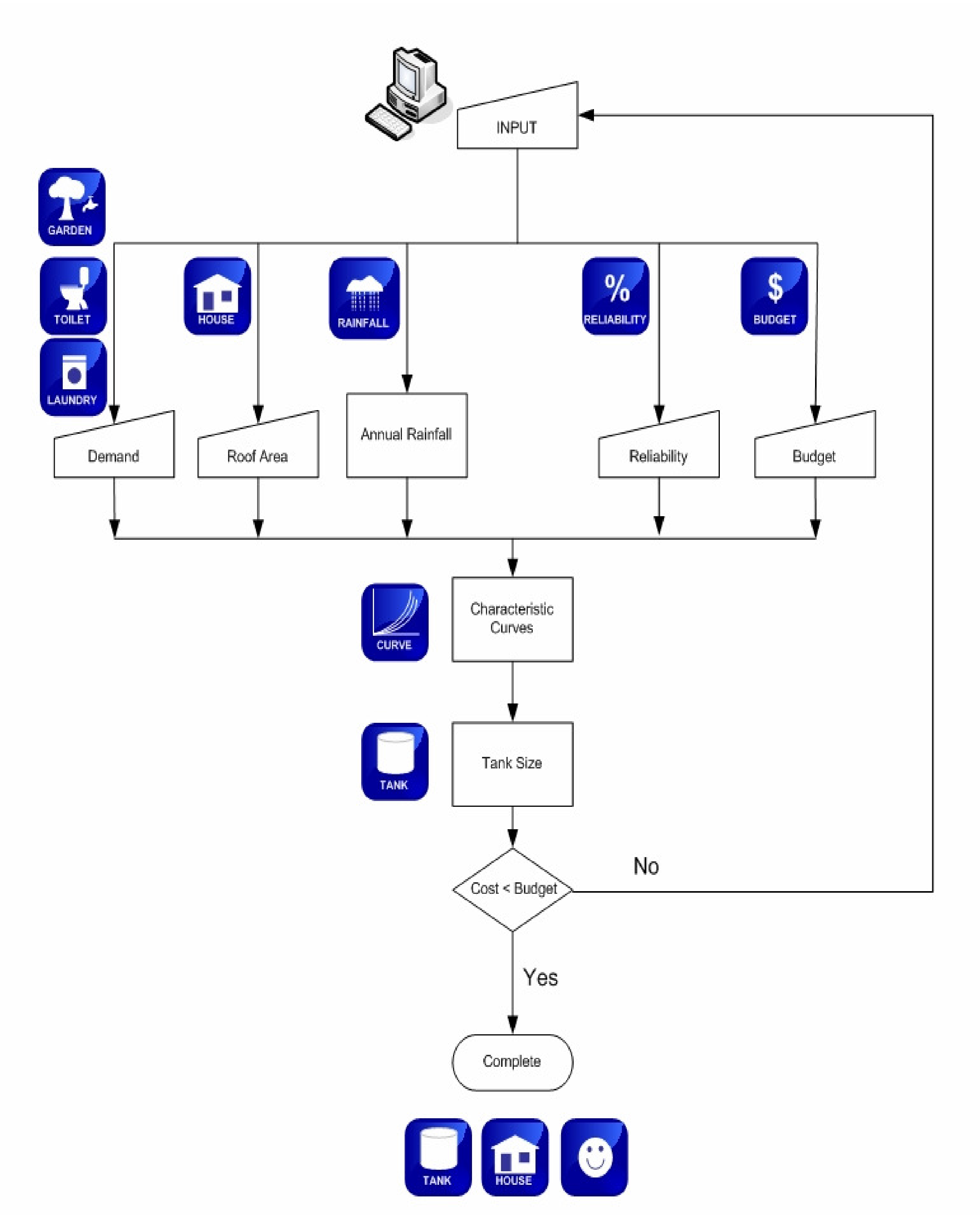

Figure 4.27 Layout of using generalized curve for selecting desired tank size

4.6 Summary and conclusions

The chapter illustrated the significance of using dimensionless analysis in order to reduce the number of independent variables that will be used in this study. The exponent method was used to obtain the dimensionless number. The three dimensionless numbers that were obtained were:

$\pi_1 = \frac{C}{A^{\frac{3}{2}}}$, $\pi_2 = \frac{D}{AR}$ and π_3 = Reliability

where,

C – Tank capacity (m^3)

D- Annual water demand (m^3/ year)

A – Roof area (m^2)

R – Mean annual rainfall, MAR (mm)

The chapter also described the development of reliability centred generalized curves to select the optimum tank size across Greater Melbourne by using the above stated dimensionless numbers. Three generalised curves were developed for 85%, 90% and 95% supply reliability. The study showed that by using these curves, it is possible to calculate the optimum tank size for a predevelopment reliability for any location in Melbourne if the demand type, area of the roof and average annual rainfall of that particular area is known.

Three distinct ranges for tank sizes were identified for MAR as the discriminator when roof area was changed from 100 m^2 to 250 m^2 for all three reliabilities 95%, 90% and 85%. The ranges were when MAR was below 550mm, between 550mm and 850mm and above 850mm (MAR<550mm; 550<MAR>850mm and MAR >850mm)

In low rainfall areas (MAR<550mm) the rainwater can be used only for toilet flushing and garden use or for combined use. The laundry use (the highest demand) can not be fulfilled in these areas with a reliability of more than 85%. However, in high rainfall areas (MAR>850mm) it is possible to meet the full demand with a high degree of reliability

This study clearly demonstrates the advantages of using the derived curves (Generalized Curve) for the installation of rainwater tanks across the Greater Melbourne area. Nevertheless, a potential tank user has to predetermine what demand the person wants to satisfy: garden (external) or internal use (toilets only or (toilet and laundry both)) and the acceptable reliability prior to selecting the appropriate size by using these curves.

The chapter also illustrates the effectiveness of the developed generalized curves by comparing the values between the water balance model and the generalized curves for various demands. From the analysis it was found that the % error for high demand is less in comparison with low demand. Although, while meeting the garden demand for 85% reliability in Arthur Creek the % difference between a tank size of 250 L (water balance model) and 420 L (generalized curve) is about 70%, in practical point of view the difference is small. Thus the % error between tank sizes derived from the water balance model and the generalized curve for various demands can not be considered significant.

One of the prime drivers for installing rainwater tanks is that it will reduce the use of potable water thus assisting balance supply and demand. However, a potential tank user and water planner will not have a feel for the effectiveness of rainwater tanks to assisting with meeting the non-potable water demand during drought periods. Chapter 5 illustrates and presents the results of the efficacy of rainwater tanks for demand management during drought periods.

Chapter 5

Simulating The Contribution Of Rainwater Tanks To Managing Melbourne's Domestic Water Demand

5.1 Introduction

As discussed in Chapter 3, one of the main aims of installing rainwater tanks is to save potable water use. Demand management can be defined as the cumulative effort of introducing relevant policies and implementing complementary actions to facilitate the saving of the amount of potable water used. Potable substitution is considered as a key element of managing demand. The key benefit of introducing demand side initiatives rather than supply side augmentations is the reduced infrastructure and environmental cost of traditional water supply augmentations such as new dams. Coombes (2002) reported that the use of rainwater tanks to supply outdoor as well as indoor demand would delay the construction of new water supply infrastructure for 34 years in the Lower Hunter region. The introduction of different rebate schemes and incentive programs, community education and the implementation of water sensitive urban design will further assist demand management. This chapter illustrates the effectiveness of rainwater tanks for managing demand during the current persistent drought.

Climate change has cast uncertainty regarding the future rainfall pattern, forecasting frequent droughts and floods in future years. In Melbourne, as a result of climate change, it is expected that Melbournians will experience warmer days and persistent dry periods regularly (Howe et al 2005). It is forecasted that there will be a significant reduction in rainfall volume with widespread variability affecting different parts of Greater Melbourne. This unexpected change in rainfall pattern can be identified by observing the rainfall and runoff over the past 10 years and in particular, 2006 which is the driest year in on record since 1913. It can be postulated that rainfall patterns in the next decade up to 2020 will be different from the past and the specific pattern of rainfall remain ambiguous. In addition, the last 10 years stream flow average is 30% below the long-term average based on data collected since early 1900's. As a result, there is a wide spread debate about the effectiveness of rainwater tanks when drought periods are expected more frequently due to climate change (in the long-term). Thus it is important to investigate the efficacy of rainwater tanks in complimenting water supply augmentation planned for the next 5 years.

Conventionally, rainwater is widely used not only for outdoor use but also for indoor use. Toilet flushing and laundry use carried out throughout the year dominate the indoor demand and garden watering dominates outdoor demand. The persistent drought in Melbourne has forced the implementation of stringent water restrictions (Level 3a) encouraging Melbournians to effectively use rainwater collected from roofs in tanks as the demand fulfilled by rainwater from a tank can result in significant mains water savings for water authorities. What is unknown is how much would it save.

The Central Region Sustainable Water Strategy study (DSE, 2006) illustrated that water demand would outstrip supply across the region by 2034. Due to rapid increase in population and the impact of climate change, there will be significant pressure on demand as well as supply. As a result, these unprecedented incidents have imposed importance on the change of thinking for future water planning. As a result, water authorities are planning to shift their focus from one major source of supply (i.e. the water supply reservoirs) to multiple non-weather dependent sources to distribute supply risks.

The chapter computes the amount of potable water that could be saved by the water authorities during the next five years, if all houses install rainwater tanks in the Greater Melbourne area. This may sound impractical but the potable water saving calculated could be scaled down from 100% to provide more realistic savings for other scenarios where less than 100% of houses carry rainwater tanks. The daily rainfall for 2004, 2005 and 2006 in concatenated series was used to recreate a somewhat worse case rainfall scenario for the next five years until the desalination plant is built.

The chapter presents the methodology adopted to calculate the amount of rainwater harvested and used across Melbourne, the meteorological scenarios tested over the next five years (until the desalination plant is commissioned in 2013), the type of demand met and the roof areas used. Conclusions will be drawn on the effectiveness of rainwater tanks in dampening water demand, thus contributing to avoiding the Level 4 restriction trigger for Melbourne over the next five years. It was decided to separate the Greater Melbourne area into three zones based on the three Melbourne water retail company serviced areas to calculate potable water savings. It was also decided to carry out analysis for different scenarios by varying the tank sizes, roof area and demand in order to calculate the percentage of potable water savings by using rainwater tanks. The rainfall patterns are reflective of rainfall received in Melbourne from 2004 to 2006.

5.2 Study areas

Three Victorian Government retail water companies namely Yarra Valley Water (YVW), South East Water (SEW) and City West Water (CWW) in Metropolitan Melbourne supply potable water and dispose sewerage and trade waste from Melbourne (Figure 5.1). Melbourne Water, also owned by the Victorian Government, is the only metropolitan water and sewerage service wholesaler for Melbourne. It sells water to the three water retailers which in turn sell services to their customers. Approximately 480,000 million litres (ML) of fresh water (average unrestricted water demand) is transported to homes and businesses each year by the retail water companies (Melbourne Water 2007). Currently this is lot lower due to restrictions.

The Greater Melbourne region is separated into three water supply zones based on the three water retail companies in Melbourne to investigate the amount of potable water that could be saved if all houses installed rainwater tanks as a demand management measure. The daily rainfall data of the 20 selected stations spreading all over Melbourne were used for the analysis. Out of these 20 stations 8 stations were in YVW zone, 5 in CWW and the remaining 7 stations in the SEW zone.

Water Services Association in Australia WSAA (2006) reported the information on the number of properties in each zone and the total residential water supplied (Table 5.1). According to the above table the residential water demand per property was highest in the YVW zone.

Table 5.1 Residential water consumption in the three water retail company zones (WSAA 2006)

Zones	RWS (ML/yr)	ARC (kL/p/yr)	NRP	ARD (ML/D)
YVW	117532	198	593596	322
SEW	103587	187	553941	284
CWW	52084	183	284612	143

RWS= Residential water supply (ML/year)

ARC= Average residential consumption (KL/person/year)

NRP= Number of residential property

ARD= Total average residential daily water demand (ML/Day)

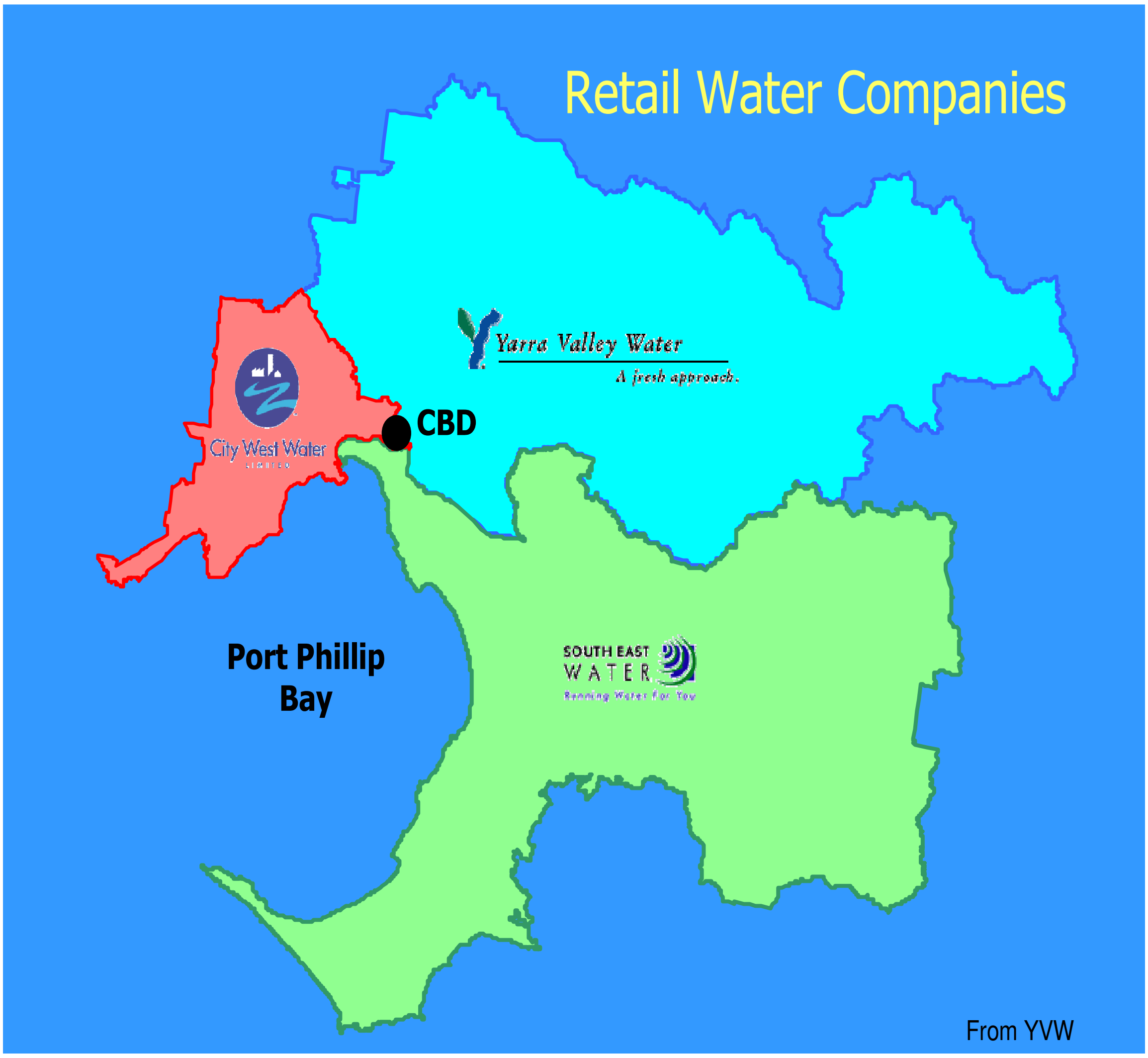

Figure 5.1 Three retail water company zones in Metropolitan Melbourne

5.3 Simulation of rainfall data

The rainfall data sequence for the next five years was synthetically created to estimate the water savings using rainwater tanks over the next 5 years. The rainfall data were concatenated to generate the required sequences of rainfall data. A similar approach is used by Melbourne Water with stream flow data in their system simulation REALM modelling work (REALM User Manual, 2005). This method was deemed suitable in the absence of generated data.

Concatenation is defined as the linking together of a consecutive series of events which was caused by external circumstances. This methodology was used together for the three consecutive years 2004 (4), 2005 (5) & 2006 (6) rainfall data to generate the next five years of rainfall data. These three years were selected as they were the years used by the Government to develop “Our Water Our Future” the Victorian Government’s Next Stage Water Plan” (DSE, 2007) which announced the decision to construct the Sugarloaf Pipeline (2010) and the desalination plant in Melbourne (2013). The three rainfall series that were used in the study are:

1. 2004, 2005, 2006 followed by 2004 and 2005 daily rainfall (45645)
2. 2005, 2006, 2004 followed by 2005 and 2006 daily rainfall (56456)
3. 2006, 2004, 2005 followed by 2006 and 2004 daily rainfall (64564)

The water savings were estimated for each retail company zone. The `Thiessen Polygon method [Thiessen and Alter (1911)]was used to calculate the average rainfall for each water retail company zone.

5.3.1 Thiessen polygon method

Thiessen polygon calculates average precipitation in a drainage basin, containing multiple rain gauges. In this study, the thiessen polygon method was used to calculate the average MAR in each retail company zone. The following procedure was followed to calculate the average rainfall in each water zone.

- Polygons were constructed by closely looking at the appropriate positions of the 20 rain gauges (latitude and longitude) (Figure 5.2).
- Rain gauge locations were plotted on a Greater Melbourne map.
- These points were inter connected by drawing straight lines between individual rain gauges.
- The lines were bisected with perpendiculars which met to form the polygons.
- The area of the polygon around each individual rain gauge was calculated and expressed as fractions of the total area.
- Each fraction was multiplied by the precipitation recorded by its rain gauge. The sum of these calculations represents total precipitation over the catchment area.

Figure 5.2 depicts the thiessen polygons used to calculate the mean annual precipitation in each zone. Based on the data used for the study the average annual rainfall computed for YVW, SEW and CWW Zones were 798mm (Table 5.2), 486mm (Table 5.3) and 709 mm (Table 5.4) respectively. This shows that there is a significant variation in rainfall across the three water authorities especially between the east and west. The analysis used daily rainfall from the three synthetically generated sequences of rainfall adjusted for the three zones using the Thiessen Polygon weights derived for the area.

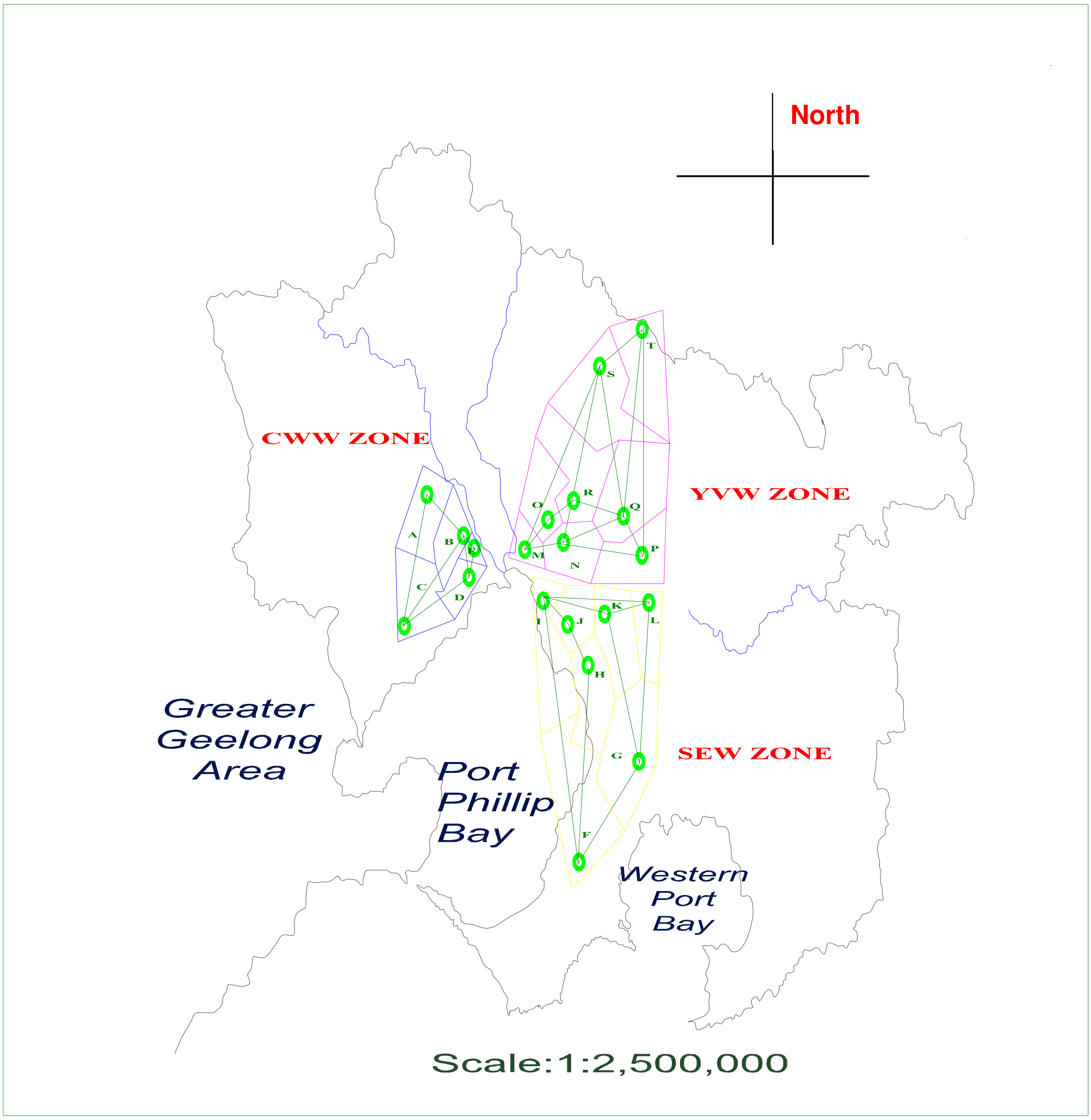

Figure 5.2: Thiessen polygons to calculate the average annual rainfall in the three water retail company zones

Table 5.2 The mean annual rainfall for the Yarra Valley Water zone (YVW) using the Theissen polygon method

Station	Thiessen area TA (km^2)	Mean annual rainfall MAR (mm)	Product (TA*MAR)
Kew	51649	690	35637810
Eastern golf club	21613	733	15842329
East Doncaster	84542	736	62222912
Kinglake	88450	1054	93226300
Arthur Creek	11255	620	6978100
Mitcham	101631	810	82321110
Mountview	62602	700	43821400
Surrey Hill	48848	725	35414800
Total MAR	470590	798	375464761

Table 5.3 The mean annual rainfall for the City West Water zone (CWW) using the Theissen polygon method

Station	Thiessen area TA (km^2)	Mean annual rainfall MAR (mm)	Product (TA*MAR)
Rockbank	53546	454	24309884
Sunshine	37008	495	18318960
St. Albans	63430	525	33300750
Altona	25359	454	11512986
Werribee	7903	453	3580059
Total MAR	187246	486	91022639

Table 5.4 The mean annual rainfall for the South east water zone (SEW) using the Theissen polygon method

Station	Thiessen area TA (km^2)	Mean annual rainfall MAR (mm)	Product (TA*MAR)
Cranbourne	85945	746	64114970
Berwick	81280	710	57708800
Sandringham	73594	700	51515800
Hampton	50973	666	33948018
Caulfield North	21900	710	15549000
Caulfield	20035	650	13022750
Notting Hill	36967	730	26985910
Total MAR	370694	709	262845248

5.4 Determination of potable water saving efficiency (WSE)

Water savings efficiency can be defined based on the amount of rainwater used for indoor and outdoor use. Villarreal and Dixon (2005) and Fewkes (2007) developed models to calculate the water saving potential of rainwater collection scheme. The studies were based on the system performance that was described by its water saving efficiency, which was a measure of how much potable water has been saved in comparison to the overall demand for rainwater. Villarreal and Dixon (2005) calculated the water saving efficiency by using Equation 5.1.

$$\text{Water Saving Efficiency (WSE)} = \frac{\left(\sum_{t=1}^{T} D_t - \sum_{t=1}^{T} M_t\right)}{\sum_{t=1}^{T} RD} \qquad (5.1)$$

where,

WSE = Water saving efficiency
D_t = Demand for rainwater (Usage)
M_t = The mains water use when there is an alternative water supply
RD= Total demand for mains water if there is no alternative water source
t = Time period (h)
T = Total duration (h)

The model developed by Fewkes (2007) is also similar to Equation 5.1. In Fewkes (2007) the water savings was calculated on daily basis (Equation 5.2). Current study uses the equation suggested by Fewkes (2007) as it is compatible with the analysis carried out in the rest of the study. The model was applied to data from each water retail company zone on a daily basis.

$$WSE = \frac{\sum_{t=1}^{n} D_t}{\sum_{t=1}^{n} RD} X\, 100 \qquad (5.2)$$

where,

D_t = Demand for rainwater (Usage)

t = Duration of time (daily)

n = Total duration of time (daily)

As mentioned in Chapter 3 the roof area (A) is the area connected to the tank. It was not possible to obtain actual roof areas of houses in each water retail company zone. In this study it was assumed that roof area of a residential house in Melbourne varies from 50m^2 to 200m^2. In addition, it was also considered that 100% of the roof area in a house was connected to the tank. It was also assumed that 50% of the houses in a zone were connected to rainwater tanks with a roof size of 100m^2, 25% to roof sizes with 50m^2 and the remaining 25% were connected to roof sizes of 200m^2. This is equivalent to 112.5m^2 average roof area. Furthermore, the demand for water directly depends on the number of people occupying the household. For this study it was assumed to be 3.

As reported earlier, in Chapter 3 after a detailed study of Melbourne's water consumption patterns, Gato (2006) recommended the use of16L/person/day (Lpcd) and 39.7 Lpcd as the best estimates of demand for toilet flushing and laundry use respectively. These numbers were used in this study to estimate respective indoor demands. Due to present Stage 3a water restrictions in Melbourne, garden watering is only permitted on two days of the week. However, in this chapter the analysis was carried out for both the pre-water restriction and post-water restriction conditions to compare the potable water savings efficiency under both conditions. As a result, in this study, it was considered that the demand for garden watering is 382 L/day (under no water restrictions) and 191L/day under present water restriction as discussed in Chapter 3.

5.5 Water saving efficiency and scenario testing

The results reported in this chapter were carried out for the Yarra Valley Water (YVW), South East Water (SEW) and City West Water (CWW) regions. The number of properties in each zone was reported in Table 5.1. As stated above, these water zones were covered by 8, 7 and 5 rainfall stations respectively. The concatenation methodology was used with 2004, 2005 and 2006 rainfall data to generate rainfall sequences for the next five years. A number of scenarios with 7 different combinations of demand for rainwater were used to compute the annual mains (potable) water savings, spillage, usage and supply reliability to satisfy different levels of demand. It was also assumed that the number of people living in a house to be equal to 3 as the water used in the toilet and laundry depend on number of occupants in the house. This number is consistent with those used by the proponents of "Melbourne 2030: Planning for Sustainable Growth (2002)". The scenarios tested were as follows:

Scenario 1: Similar size tank (3kL) is installed across the zones to meet different water demands. The water is drained to the tank from the same proportion of roof areas. In calculating the average roof area in the zone it was assumed that 50% of the houses in the zone were connected to 100m^2; 25% to 50m^2 and 25% to 200m^2. This is equivalent to 112.5m^2 average roof area.

Scenario 2: Same demand (toilet flushing, garden watering and laundry use) with varying tank sizes. The water is drained to the tank from the same proportion of roof areas as in Scenario 1. The tank size varied from 1kL to 5kL. The roof area used is equivalent to 112.5m^2.

Scenario 3: Same size of tank (3kL) is installed across the zones with different water demands and roof areas. The demand value varies from high demand (toilet flushing, garden watering and laundry use) to low demand (only garden). The roof area was also varied from 50m^2 to 200m^2.

Scenario 1

Scenario 1 assumes the tank size to be 3kL. Tables 5.5, 5.6 and 5.7 depict the relationship between reliability, spillage, usage and annual mains water savings for the rainfall patterns 45645, 56456 and 64564 with the data for the YVW region. The percentage saving of water is similar in magnitude for all three rainfall series. The above relationship for SEW and CWW are shown in Appendix E (Tables E1 to E6). The above tables show that by using the rainwater tank for meeting the demand of garden watering or toilet use, it is possible to deliver maximum reliability in comparison with laundry demand or combination of these demands.

In case of garden watering, the water saving efficiency for a 3kL tank was found to be only 4% due to low garden water use during present water restriction. It is important to note that garden usage is taken to be compatible with the prevailing Level 3a water restrictions in Melbourne. However, low usage and high spillage indicates that a significant amount of rainwater is wasted as there is no demand for garden use for 6 months of the year from April to September. Furthermore, it is not necessary to increase the tank size in order to store more water and reduce the spillage as the supply reliability for garden use and toilet use is close to 100%. Tank water used for meeting high demands (e.g. toilet + garden+laundry) minimizes spillage and maximizes usage whilst dropping supply reliability significantly. However, if there is no rainwater to meet the demand, the deficit will be supplemented with backup mains water, especially if the rainwater is used in the laundry or in the toilet. The table also reports on the annual potable water savings depending on the demand for rainwater. The main difference between supply reliability among the three water retailers is that supply reliability is higher in YVW in comparison with the remaining two water zones. This is mainly due the variation in rainfall patterns of the zones.

Table 5.5 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 45645) for the YVW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	67.8	16.8	44.8	23
T+L	76.4	17.6	46.1	24
T+G	97.0	40.8	25.4	13
G+L	80.0	25.0	40.6	20
T	99.8	47.6	17.5	9
L	90.3	26.7	39.6	20
G	99.8	56.7	8.8	4

Table 5.6 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 56456) for the YVW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	68.2	7.5	46.2	23
T+L	75.5	8.1	46.6	23
T+G	98.2	30.7	25.5	13
G+L	82.4	13	41.4	21
T	99.9	39	17.5	9
L	91.6	15.8	39.6	20
G	99.6	47.8	8.7	4

Table 5.7 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 64564) for the YVW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	66.2	3.5	44.3	23
T+L	73.5	3.5	44.1	23
T+G	96.9	23.5	25.6	13
G+L	80.9	6.3	40.7	20
T	99.9	31.4	17.6	9
L	90.3	8.7	39.2	20
G	99.9	39.9	9.0	4

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Based on the above analysis the high potable water savings could be achieved if rainwater is used in the laundry or laundry use together with toilet and/or garden. If the rainfall pattern for the next five years follows a similar pattern to the last three years, the potable water usage could be reduced by 20% to 24% of current consumption over the years if a rainwater (3kL) tank is used at to meet least laundry demand and if 100% of the houses have mandated rainwater tanks installed. Similar results were obtained from the other two water zones (D1 to D6). However, if the tank penetration is less than 100%, the 16% to 24% savings should be adjusted accordingly. For example, if 50% of the houses have rainwater tank of 3kL, then the cumulative savings over the 5 years would be around 8% to 12%.

Relationship between potable water saving efficiency (WSE) for a 3kL tank for the three water zones in three consecutive years (Rainfall pattern 45645) is shown in Figure 5.3. The Figure clearly demonstrates that WSE was the lowest in 2006. That is because MAR in year 2006 was significantly lower than in 2004 and 2005 (20% and 17% lower for YVW). This contributed to the reduction in total WSE within the next 5 years. However, the rainfall values in Melbourne are continuing to decline.

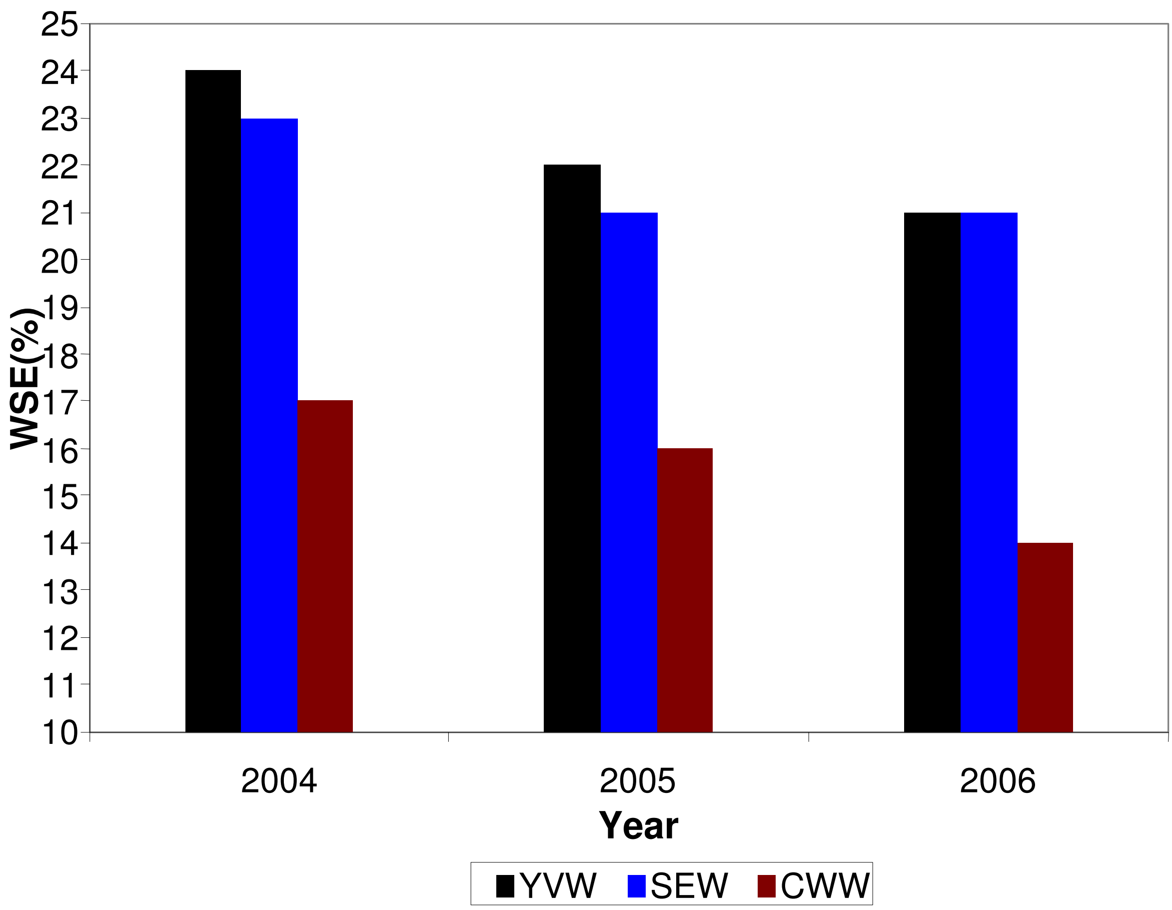

Figure 5.3 Relationship between water saving efficiency for a 3 kL tank for the three water zones in three consecutive years (Rainfall pattern 45645)

Scenario 2

Scenario 2 varied the tank sizes from 1kL to 5kL. However the roof sizes remained as assumed in Scenario 1. The number of occupants in a house was also varied from 1 to 3 in order to vary the indoor demand for rainwater in a house. The WSE was calculated for toilet, laundry and garden use as it is the highest demand that could be expected for rainwater use in a house. Figures 5.4, 5.5 and 5.6 detail the relationship between spillage, usage, water savings efficiency and tank size for all three water zones.

As expected, the ratio of spillage/usage decreases with increase in tank size. Moreover, with the increase in tank sizes the water saving efficiency increase. The figures further illustrate that due to increase in demand, the spillage/usage increases which indicates that the stored water in the tank will spill more due to less usage. In addition, for a household of low demand (1 person household) the WSE is considerably lower than the household of 2 or 3 people. As a result, while the tank is installed to meet the low demand irrespective of water zones and tank size, the WSE will be low because of unused water from the tank.

In addition, Figures 5.4, 5.5 and 5.6 illustrate that with increase of people in the household spillage to usage ratio deceases. Moreover, water saving efficiency also increases considerably due to increase in indoor demand. Hence, in terms of potable water savings, to maximize the benefit of using the rainwater from a tank, the demand for water has to be increased.

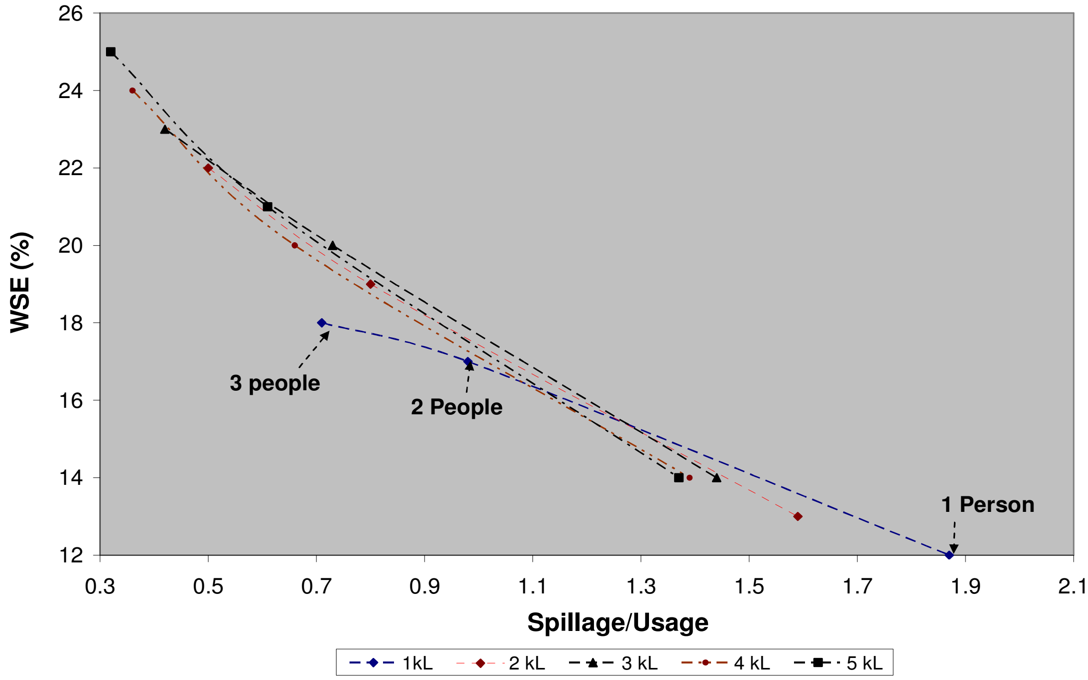

Figure 5.4 Relationship between spillage, usage, and water saving efficiency for different tank sizes and different number of people in a house (YVW) [Upper end of the graph is for 3 people and lower end is for 1 person]

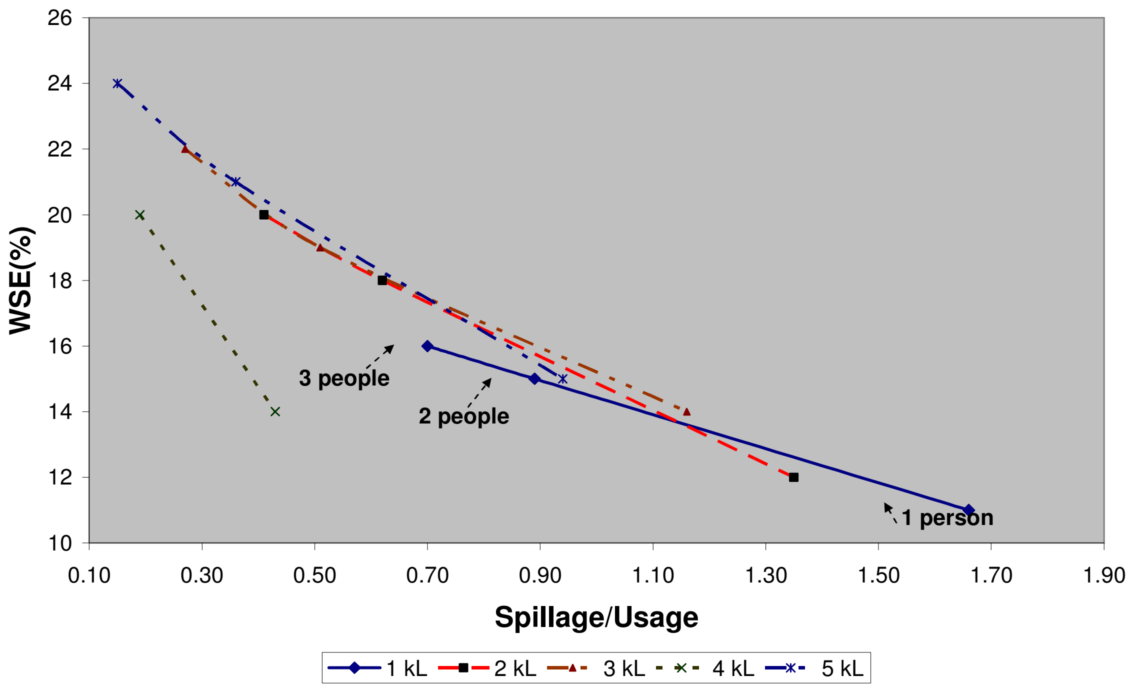

Figure 5.5 Relationship between spillage, usages, and water saving efficiency for different tank sizes and different number of people in a house (SEW) [Upper end of the graph is for 3 people and lower end is for 1 person]

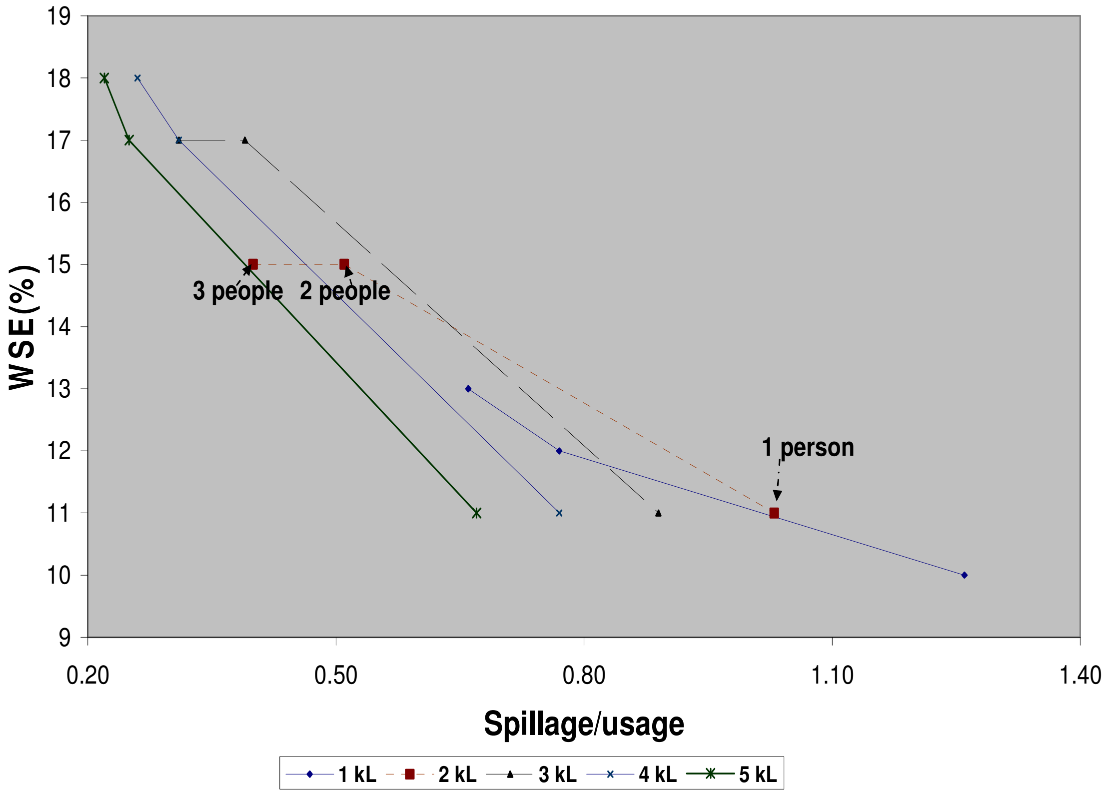

Figure 5.6 Relationship between spillage, usage, and water saving efficiency for different tank sizes and different number of people in a house (CWW)[Upper end of the graph is for 3 people and lower end is for 1 person]

Scenario 3

Scenario 3 was carried out to observe the relationship between the WSE and different roof areas for a 3kL rainwater tank installed across the three regions YVW, SEW and CWW regions. Roof areas were changed assuming roof areas in the zones vary from 50 m^2 to 200 m^2. Four types of demand patterns were also considered in the analysis. Figures 5.7, 5.8 and 5.9 show that for high rainwater demand (T+G+L and T+G) WSE varies considerably due to variation of roof areas whereas in case of low rainwater demand (T and G) irrespective of the roof size, the WSE stays relatively constant . This indicates that the water usage is the same and water is collected from bigger roof areas. In this case it is evident that there is potential to use rainwater for more than toilet and garden use in the three water zones.

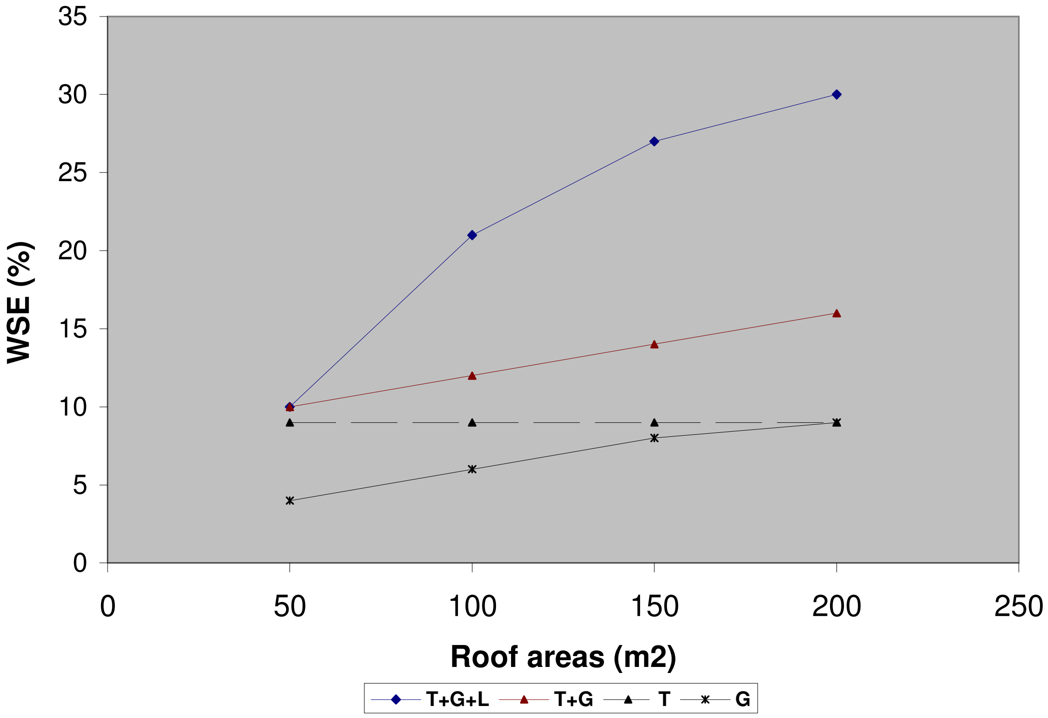

Figure 5.7 Relationship between WSE and roof areas for a constant tank size of 3 KL (YVW)

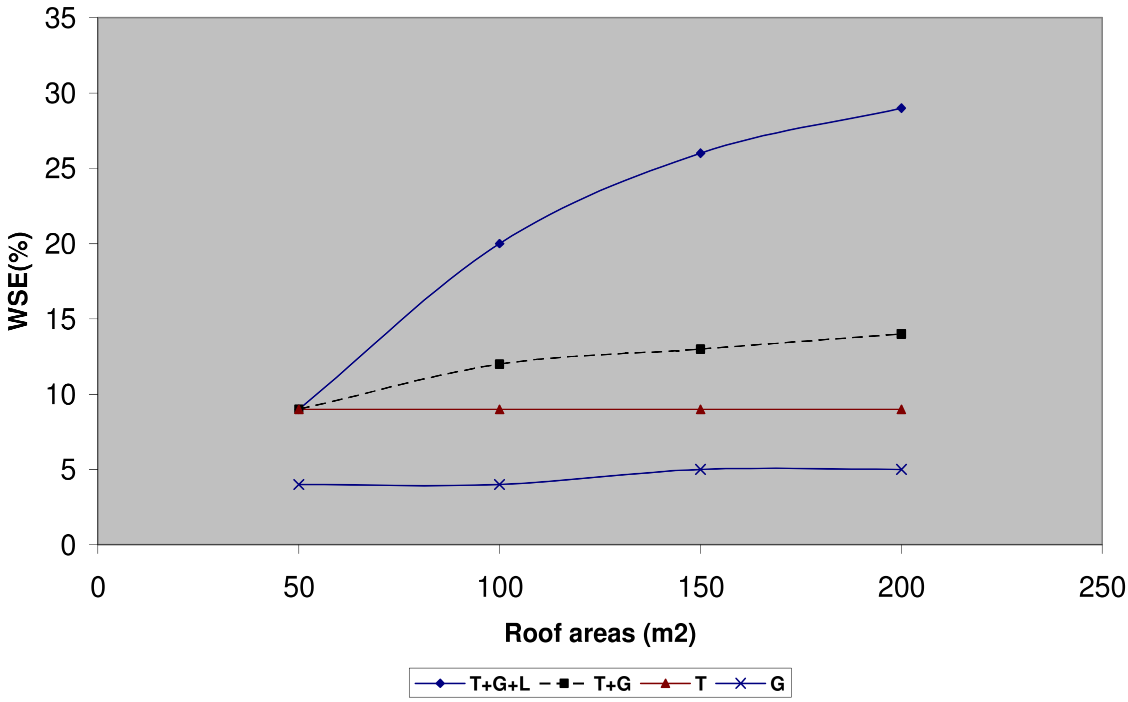

Figure 5.8 Relationship between WSE and roof areas for a constant tank size of 3 KL (SEW)

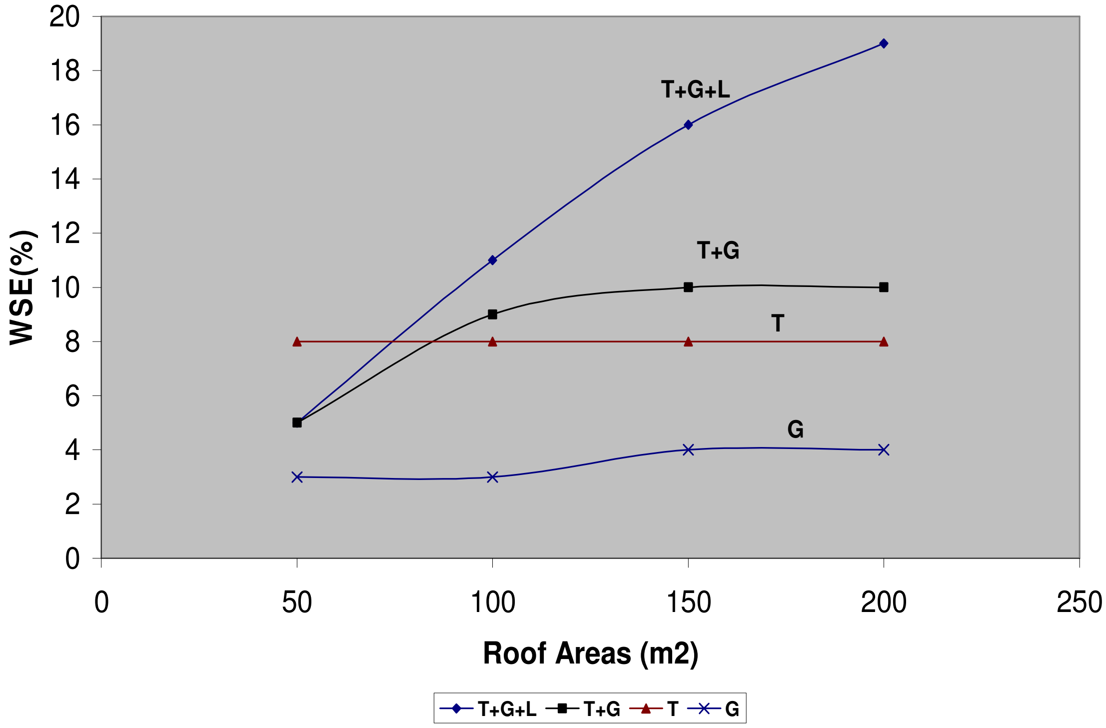

Figure 5.9 Relationship between WSE and roof areas for a constant tank size of 3 KL (CWW)

5.6 Comparison of Water Saving Efficiency

The water saving efficiency in the three water zones need comparison. Tables 5.6, 5.7 and 5.8 report the comparison of water saving efficiencies (WSE) for the three water retail company zones for the rainfall pattern 45645 if 1 kL, 3kL and 5kL tanks are installed in all houses in each zone. The roof area is assumed to be equivalent to 112.5m^2. The results from the tank sizes less than 1kL are not presented as the WSE does not vary considerably with the demand for water for a small tank (see Figure 5.4). A tank size greater than 5kL was also not considered as it is considered too large for a domestic house. A potable water savings of between 20% to 25% could be obtained from YVW and SEW zones if 3kL to 5kL rainwater tanks were installed for laundry or laundry, toilet and/or garden use. The number of households was 3 people. However, for the CWW region the annual water savings could only be around 16%. The average annual rainfall in YVW and SEW zones were taken as 798mm and 709mm respectively, where as for CWW the annual rainfall was only 486mm. The average rainfall value in the local area clearly reflects on the amount of potable water savings that could be achieved if rainwater was used to supplement the potable water usage.

Tables 5.8, 5.9 and 5.10 show that there is not much difference in WSE with the tank sizes if rainwater is used only for toilet flushing or garden watering. As a result, for low demand irrespective of tank size and water retail company zones the WSE will remain almost constant. However, for high demand there is a considerable variation in WSE due to variation of MAR (water zones). In addition, for a 3kL and 5kL tank and for a particular demand, the WSE change is insignificant in each zone. Hence, it can be stated that for a small tank size (1kL), irrespective of zones, the WSE will be considerably low in comparison with large tank sizes (3kL or 5kL) in order to meet high demand. However, from a in customers point of view, there will be a considerable variation in supply reliability in all three water zones which can be distinctly visible form Tables 5.3 to 5.5 and Appendix E (Tables E1 to E6). As a result, a potential customer will not have sufficient rainwater to meet high demands in majority of the time in a year. In case of CWW the supply reliability can be as low as 50% while meeting the high demand, even if one invests in a 3kL tank. A potential customer of a rainwater tank will have legitimate concerns when deciding to invest on a rainwater tank if the supply reliability is low. The installation of a tank will only achieve a small supply reliability.

Table 5.8 Water saving efficiency in three water retail company zones in the Greater Melbourne area if 1kL tanks are installed in all houses (Average roof area = 112.5km^2)

Demand**	**Water Savings Efficiency (WSE) (%)**		
	YVW	**SEW**	**CWW**
T+G+L	17	16	13
T+L	17	16	13
T+G	10	7	13
G+L	16	15	13
T	9	9	9
L	16	15	13
G	4	3	3

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Table 5.9 Water saving efficiency in three water retail company zones in the Greater Melbourne area if 3kL tanks are installed in all houses (Average roof area = 112.5km^2)

Demand**	Water Savings Efficiency (WSE) (%)		
	YVW	SEW	CWW
T+G+L	23	22	17
T+L	24	22	17
T+G	13	13	12
G+L	20	20	16
T	9	9	8
L	20	20	16
G	4	5	3

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Table 5.10 Water saving efficiency in three water retail company zones in Greater Melbourne if 5kL tanks are installed in all houses (Average roof area = 112.5m^2)

Demand**	Water Savings Efficiency (WSE) (%)		
	YVW	**SEW**	**CWW**
T+G+L	25	24	18
T+L	25	24	18
T+G	13	14	13
G+L	22	22	18
T	9	9	8
L	21	21	18
G	4	5	4

**T = Toilet Flushing, G = Garden watering and L = Laundry use

5.7 Potable water savings (under no water restriction)

It was also decided to estimate the volume of potable water savings if rainwater was used for toilet flushing, garden watering and laundry use before water restrictions were placed. The prime difference between the with and without water restriction periods is the daily garden water use in a household. As reported earlier, Stage 3a water restrictions prohibit watering lawns which automatically reduces garden usage by 50%. As a result, there will be a variation in the potable water savings achieved using a rainwater tank between pre and post restriction period. In the current study it was assumed that when water restrictions are not in place, Melbournians used potable water for garden watering 6 months of the year (October – March) on a daily basis. Table 5.11 presents the relationship between reliability, spillage, usage and annual mains water savings for the rainfall patterns 45645, for the YVW region. By comparing the values in Table 5.3 and Table 5.11, during pre water restriction period the spillage of water and water supply reliability have reduced significantly.

The water saving efficiency (WSE) for garden watering has reduced from 12% to 4% due to water restrictions in place. However, in the case of weekly toilet and laundry demand there is no variation in WSE as water restrictions do not apply to toilet and laundry use. Tables 5.12, 5.13 and 5.14 depict the WSE that will be achieved using rainwater tanks for the three water retail company zones for the rainfall pattern 45645 if 1kL, 3kL and 5kL tanks are installed in all houses in each zone. The study assumes no water restrictions are in place. The roof area is also assumed to be equal to 112.5m^2 to ensure consistency with previous analysis. When above results are compared with the results presented in Tables 5.6 to 5.8, the only difference is WSE that can be observed is for garden watering. As an example, when rainwater is used for garden watering, it is possible to obtain a 14% WSE under no water restrictions in Melbourne by using a 5kL tank. This has reduced to 4% during the water restriction condition. As reported in Chapter 2, the water demand for garden watering was 35% before the restrictions were in place (Melbourne Water 2006a). The rainwater tanks can not meet the full demand and supply during summer months. The reason for this difference is that in case of garden watering, WSE has decreased a lot due to water spill. The WSE to meet the demand of toilet flushing, garden watering and laundry use is less than under no water restriction condition in comparison with water restriction condition in the SEW zone. During the high demand prior to applying water restrictions, there is insufficient water in the tank to meet the demand, thus eventually affecting the WSE.

Table 5.11 Relationship between reliability of supply, spillage, usage and potable water saving efficiency (WSE) from for a 3kL tank (Rainfall pattern 45645) for YVW before water restrictions were implemented

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	49.4	9.7	43.5	22
T+L	76.4	17.6	46.2	24
T+G	63.7	26.7	31.7	16
G+L	56.5	15.4	41.0	21
T	99.8	47.6	17.5	9
L	90.3	26.7	39.6	20
G	67.5	35.7	23.8	12

Table 5.12 Water saving efficiency in three water retail company zones in the Greater Melbourne area if 1kL tanks are installed in all houses (Average roof area = 112.5km^2) before water restrictions were implemented

Demand	Water saving efficiency (WSE) (%)		
	YVW	SEW	CWW
T+G+L	17	15	13
T+L	17	16	13
T+G	13	11	13
G+L	17	11	13
T	9	7	9
L	16	15	13
G	9	7	7

Table 5.13 Water saving efficiency in three water retail company zones in the Greater Melbourne area if 3kL tanks are installed in all houses (Average roof area = 112.5km^2) before water restrictions were implemented

Demand	Water saving efficiency (WSE) (%)		
	YVW	SEW	CWW
T+G+L	22	21	16
T+L	24	22	16
T+G	16	16	12
G+L	21	20	16
T	9	9	8
L	20	20	16
G	12	11	10

Table 5.14 Water saving efficiency in three water retail company zones in Greater Melbourne if 5kL tanks are installed in all houses (Average roof area = 112.5m^2)

Demand	Water Saving Efficiency (WSE) (%)		
	YVW	SEW	CWW
T+G+L	25	23	18
T+L	25	24	18
T+G	18	18	13
G+L	23	23	18
T	9	9	8
L	21	21	18
G	14	14	12

5.8 Summary and conclusions

The study analysed the effectiveness of rainwater tanks and estimated the volume of potable water saved if the current drought period that Melbournians are currently facing continues until 2013. A desalination plant is scheduled to be constructed and commissioned by then. The observed rainfall for 2004, 2005 and 2006 was used to generate possible rainfall sequences for the next five years (until the desalination plant is commissioned) to supply Melbourne. The highest potable water savings could be achieved when rainwater is used in the laundry and/or for toilet flushing and in the garden. The analyses revealed that potable water saving of 21% to 23% could be obtained from YVW and SEW zones if rainwater is used in the laundry and 3kL tank installed in all houses (100%) throughout the zone with rainwater draining from an average roof size of 112.5m^2. CWW area could save only a round 17% when scenarios similar to above were applied. This is because the annual rainfall is around 30% lower in the western region of Melbourne. In addition, this study has introduced the concept of reliability and shown it requires attention when selecting an appropriate rainwater tank size for a property. From the analysis carried out in this chapter it can be stated that for high demand (laundry and/or together with toilet and garden) irrespective of the water zones (YVW, SEW and CWW) the supply reliability that can be met with a tank will be low.

The total amount of water saved does not vary with roof sizes assumed for the zone if the demand for rainwater is low and used only for garden watering or to flush the toilets. However, with higher demands (when laundry use is included) the water supply reliability (WSE) varies considerably with the roof area.

The above stated case studies demonstrated that there are significant opportunities for a city like Melbourne, which is suffering from prolonged drought, to introduce rainwater harvesting in a majority households to save water. Lack of space in some properties would make installation of tanks prohibitive. However, recent streamlined designs have made it possible to place tanks in most properties harvesting roof water. The anticipated savings would be proportionally discounted if tanks cannot be installed in every property. An 8% to 12% saving could be achieved if 50% of the houses in Melbourne installed at least a 3kL tank.

The study also analysed the amount of rainwater that could be used effectively if no water restrictions are in place. The study showed that there is a considerable impact on the use of rainwater due to Stage 3a water restriction which permit garden watering only for two days in a week. In addition, lawn watering is prohibited during the 3a water restriction period. The study showed that a 5kL rainwater tank will supply 14% of the garden water demand when there are no water restrictions (That is watering the garden 6 months of the year on a daily basis). However, when the water restrictions are in place rainwater tanks will supply only 4% of the demand. As a result, it can be stated that under water restriction conditions the rainwater tank can not be used effectively for garden watering due to less demand and hence spill often.

As mentioned in Chapter 3, an aspirational water conservation target has been set by the Victorian Government with a view to reducing the per capita consumption by 15%, 25% and 30% by 2010, 2015 and 2020 respectively. The chapter demonstrates that if every household of Melbourne installs a 3kL rainwater tank for non potable purposes, a water savings between 16% to 24% could be achieved based on MAR based on 2004, 2005 and 2006. Active participation of Melbournians in rainwater harvesting programs facilitation achieving the stretched water conservation targets.

However, in addition to the potable water savings efficiency of a selected rainwater tank, a potential customer for the rainwater tanks must also think about the quality of rainwater. The quality of water stored in the rainwater has been explained in details in Chapter 6.

Chapter 6

Impacts Of Rainwater Tanks On Managing Stormwater Runoff Harvesting And Quality

6.1 Introduction

As discussed in Chapter 5, rainwater tanks can be used effectively to partially meet the domestic water demand even during drought periods. However, there are some obstacles which may act as deterrents to rainwater harvesting. A number of researchers have reported issues related to water quality in the rainwater tank (Taylor et al 1999, Abbott et al. 2007). Although rainwater remains an easily available resource in houses due to perceived poor water quality, people are reluctant to use this abundant water source. There is an ongoing debate between advocacy groups and the Department of Human Services responsible for public health over the appropriateness of using rainwater tanks for domestic use.

The popularity of rainwater use in Australia completely depends on the individual's preference. It is a fact that the quality of reticulated water supplies in major cities of Australia is far superior to water stored in rainwater tanks. However, due to persistent drought and implementation of stringent water restrictions in Melbourne the using of alternative water sources have been encouraged. On the other hand, it is also important to ensure acceptable rainwater quality. One of the options to reduce any potential risk from rainwater stored in the tank is to restrict the water use for non potable purposes. It is a common understanding that the water quality requirements for non-potable uses are considerably lower than that for drinking water. However, an enhanced understanding of rainwater tank quality will guide actions to improve quality and provide flexibility to expand use for potable purposes if necessary in the future.

The aim of this chapter is to better understand the quality of rainwater stored in the tank from relevant contemporary literature carried out by different researchers. In addition, the possible reasons of contamination of rainwater stored in the tank will be identified from the recent studies. WSUD (2005) considered rainwater tanks as an effective treatment device with a view to mitigating the impact of stormwater on receiving water by reducing stormwater runoff volume and pollutants entering the drainage system. The chapter will also focus on the effectiveness application of rainwater tanks as a potential water sensitive urban design element to effectively manage stormwater. This will be carried out by using the MUSIC model (MUSIC April 2007).

6.2 The water quality of rainwater stored in the tank

The quality of rainwater depends on number of factors such as: the type of the roof, type and design of the rainwater tank and the quality of rainfall itself. The Australian drinking water standards do not provide information on the quality of water for non-drinking purposes. In addition, there is scarcity of knowledge in relation to processes occurring in rainwater harvesting systems affecting quality (Spinks et al 2003).

The stored water in the tank can be easily contaminated due to following reasons**:**

- Concentration of metals and non metals on roofing materials and the atmosphere
- Contamination from animals and birds including droppings
- Contamination due to type and design of tank (access to animals and corrosive metals)
- Contamination due to lack of maintenance

6.2.1 Concentration of metals and non metals on roofing materials and the atmosphere

Gee (1993) reported on water pollution due to lead based paints and coatings on the roofs. Although, potable use of rainwater is discouraged in Cities, the use of lead based paints and tar based coatings on the roofs will create an adverse impact on the taste of the water.

Jenkins and Pearson (1978), Randall (1978) and Magyar et al (2006) stated that in urban and industrial areas lead concentrations always exceeded the limit set by the World Health Organization (WHO) guidelines. Hart and White (2006) reported the presence of high zinc concentration caused by metal roofs and roofing materials in comparison to tiled roofs. However, according to above studies copper concentration did not vary significantly due to variation of roofing materials.

The most commonly used roofing materials in Australian homes are: galvanized iron, Al-Zn coated steel, cement tiles and pre-painted steel (Morrow et al 2007). The study considered the differences in the use of roofing materials between urban and rural areas and the tank water quality as well as samples collected from tanks with different roofing materials. The study reported that concentration of cadmium, molybdenum, potassium, rubidium, selenium and vanadium varied significantly with different types of roof materials.

Martin et al (2007) analysed the water quality of a 2 kL tank from a roof area of 25m^2. The study found that the water quality of precipitation was of high quality. However, the water collected from the roof surface showed the presence of considerable lead and manganese and was the major source of bacterial pollutants. However, water from the tank's point of supply showed an improvement in quality in comparison with rainwater entering the tank, and the surface interface layer. The study recommended by analysing the result that harvested rainwater would be of acceptable quality for toilet flushing and outdoor use (non potable use).

6.2.2. Contamination from animals and birds including droppings

Abbott et al. (2007) reported on a number of roof water supply systems surveyed in New Zealand and their deficiencies. According to the above study, faecal contamination from birds remains one of the major pollutants.

The study reported on the following reasons for faecal contamination

- Inappropriate maintenance of the tank and roof catchment
- Inappropriate design of delivery systems and storage tanks
- Incapability to adopt physical measures to safeguard the water against microbiological contamination

The roof collected rainwater often carries high levels of faecal contamination. Several contemporary studies showed that presence of coliform and faecal coliform in rainwater is a common phenomenon. Abbott et al (2007) reported the high level of faecal contamination presence in 560 samples. Ahmed et al (1998) observed the bacterial growth on the internal surface of storage tanks. The study reported that sedimentation of small amount of organic matter could increase the build-up of nutrients at the bottom of the tank and hence accelerate the growth of bacteria in the tank. Furthermore, Evans et al (2006) reported the presence of airborne micro-organisms which increased the bacterial load in the roof water.

Taylor et al (1999) reported the presence of *Salmonella* in an inadequately maintained rainwater tank in Rockhampton, Queensland. The study found that green tree frogs and mice were the prime reasons for presence of *Salmonella*. Furthermore, it was determined that absence of mesh screen on all inlets and outlets facilitated this mishap. Reptiles and birds could also contribute to the presence of *Salmonella* in rainwater (Freidman et al 1998, Cunliffe 2004).

Simmons et al (2001) reported that different gastrointestinal diseases could occur from a water tank due to pathogens such as *Salmonella, Campylobacter, Giardia and Cryptosporidium.* O'Toole et al (2006) presented the water quality of rainwater collected from roofs to determine the concentration of different bacterial components in 6 different localities around Australia. The study analysed the samples for *E. coli, total coliforms, enterococci, Clostridium perfringens, Salmonella spp, Campylobacter spp, Legionella spp and Aeromonas spp.* The study revealed the presence of *Campylobacter and Salmonella* spp in some rainwater tanks. The existence of these bacteria raises the possibility of gastrointestinal infection. The study reported that the use of first flush diverters should be encouraged to improve the quality of rainwater. In addition, the study found that wind direction and rainfall intensity had significant impact on roof-collected rainwater.

Besides this, Abbott et al. (2006) reported that 50% of the roof collected rainwater samples (out of 560) in New Zealand exceeded the minimal acceptable standards for microbiological contamination. In addition, the study reported that 30% of the samples showed evidence of heavy faecal contamination. The study concluded that the likely sources of the faecal contamination were faecal material deposited by birds, frogs, rodents and possums, and dead animals and insects, either on the roofs or in the gutters, or in the water tank itself.

6.2.3. Contamination due to type and design of tank

Magyar et al (2007) reported on a number of rainwater tank design factors that could significantly deteriorate out-flowing water quality. They are:

- type of inlet, which can affect sediment mixing intensity;
- water level and height of outlet from the base of the tank; and
- volume of sediment accumulated over the time .

The study investigated nine full sized rainwater tanks in suburban Melbourne and found that sediments at the base of the tanks contained high concentrations of metals. In addition, Handreck (1979) pointed out that the use of galvanized tanks might cause zinc toxicity in plants. As a result, the study encouraged the use of concrete and fibreglass tanks to eradicate the toxicity problems.

Jenkins and Pearson (1978) found that quality of roof runoff could be increased by diverting the first flush of runoff and preventing the entry to rainwater tank. The study suggested that for a roof area of $100m^2$ the first 25litres should be diverted and in case of $200m^2$ roof the volume should be 50litres. In addition, Yaziz et al (1989) recommended the diverted volumes to be on one litre per three square meters of roof.

6.2.4. Contamination due to lack of maintenance

It is important to maintain the rainwater tank to prevent water quality deterioration. Abbott et al (2007) stated from a survey result that people did not have adequate information regarding tanks and gutter cleaning which was a major concern for ensuring proper maintenance of the tank. The survey found that 10% to 30% of the people participating in the survey did not carry out any gutter and tank cleaning. The study revealed that 52% of the participants did not take any physical measures (eg. first flush/ gutter guard/ tank inlet screen/ sludge trap/ tank vacuum system) to improve the water quality in the tank

Coombes (2002) and Cunliffe (2004) stated that rainwater collected from inner city industrial area and stored in tanks was of acceptable quality for non–potable use. The study reported that rainwater used in hot water systems was compliant with Australian drinking water guidelines. The quality of rainwater at the point of supply was found to be significantly improved in comparison with the rainwater quality from the roof runoff and subsequently in the surface of the tank, the study observed.

Nevertheless, Coombes (2002) stated that the presence of coliforms in rainwater tanks could not be the ideal indicator to determine quality of water. Coombes (2002) stated that coliform bacteria could occur naturally in the environment and might not have direct relationship with the roof collected water in the tank.

Jayaratne et al (2006) illustrated the quality issues affecting the rainwater as a source of hot water for household uses. The trail rainwater collection system in this study used three 750 litre capacity rainwater tanks in series with a pump, a filter and UV disinfection unit downstream of the tank. The study carried out the test for 30 parameters which covered physical, chemical and microbiological characteristics for a period of 1 year. The study noted that *Salmonella, Campylobacter and Legionella Bacteria* were not detected in the samples. However, the presence of *E.Coli*, total coliforms, and plate count bacteria was found in all samples in the rainwater tank. Interestingly, *E.Coli* presence was not found in the samples collected at the hot water tap in the kitchen. Furthermore, elevated levels of lead, colour and low p^H was observed during the experiment. The study revealed that UV treatment might not be necessary if the hot water system maintains a temperature above 60 degree Celsius.

6.3 Water borne illnesses

As mentioned earlier, rainwater can be contaminated through faecal material deposited by different birds, frogs, rodents and dead animals. Moreover, leaching of heavy metals from roofing materials can create contamination in rainwater runoff and subsequently in the stored water in the tank. Waterborne diseases are primarily caused by pathogenic microorganisms which are directly transmitted when contaminated drinking water is consumed. As a result, there will be health concerns while using rainwater from the tank.

Abbott et al (2007) noted that many organisms which were isolated from contaminated roof water can cause infections and in some extreme cases gastrointestinal diseases. The study reported that pathogens such as *Salmonella, Campylobacter, Giardia and Cryptosporidium* can cause severe gastrointestinal diseases. Table 6.1 depicts the diseases that can be transmitted form the above micro organisms.

However, the CRC for Water Quality and Treatment in their publication "Public health aspects of rainwater in urban Australia" reported only about only two epidemiological studies which compared overall rates of gastrointestinal illness between people drinking rainwater and people drinking from reticulated water supplies in South Australia. Those studies examined children in the 4 to 6 year age group. The report indicated that those two studies gave completely different results but overall suggested that consumption of water from rainwater tanks would not pose a health risk. As a result, there is no conclusive evidence of outbreak of gastrointestinal diseases only due to consumption of water from rainwater tanks.

Table 6.1: Different water borne illnesses from pathogens

Pathogens	**Characteristics**	**Disease/ illness**
Salmonella	Rod-shaped enterobacteria	Typhoid, paratyphoid
Campylobacter	Spiral, microaerophilic bacteria	Campylobacteriosis (Diarrhoea, abdominal pain, fever, cramping)
Giardia	Flagellated protozoan parasite	Diarrhoea
Cryptosporidium	Protozoa	Cryptosporidiosis (Diarrhoea, stomach pains and low fever)

6.4 Water quality management

Increased runoff as well as the discharge of polluted stormwater resulting from catchment urbanisation will adversely affect the flora and fauna of receiving waters. As a result controlling the excess surface water as well as quality improvement is important when designing urban drainage infrastructure. Lloyd et al (2001) revealed that by controlling stormwater pollutants at their source could provide the following advantages:

- Reduction of hydraulic loading on receiving water
- Greater ability to attenuate surface flows
- Reduction of pollutant loads to downstream local treatment facilities (such as wetlands)

WSUD (2005) considered rainwater tank as a potent component of stormwater mitigation because it can protect urban streams by reducing stormwater runoff volume and thus pollutants from reaching downstream waterways. As a result, a rainwater tank can be considered as a source control method that can be incorporated into the residential drainage design to treat roof runoff prior to discharging to receiving waters. Furthermore, it will also reduce pollutant loads flowing into the drainage system. In this study to determine the effect on receiving water, of pollutant loads and concentrations were modelled for a household connected to a rainwater tank as a stormwater treatment device. The Model for Urban Stormwater Improvement Conceptualisation (MUSIC April 2007), which was developed by the Cooperative Research Centre for Catchment Hydrology (CRCCH), was used with a view to assessing the performance of the rainwater tank in managing stormwater (quantity and quality) otherwise draining to receiving water.

The MUSIC model has three types of nodes namely: source node, treatment node and receiving node. In this analysis the source node is a typical household of Melbourne in which the roof is considered to be connected to the gutter to collect the rainwater in the tank. The treatment node will be the rainwater tank and the receiving node will be the urban drainage system.

6.5 Application of MUSIC model to manage stormwater quantity and quality

In this study a typical house of Greater Melbourne was considered in the analysis. Figure 6.1 depicts the MUSIC model configuration used to treat the stormwater from a typical household of Melbourne.

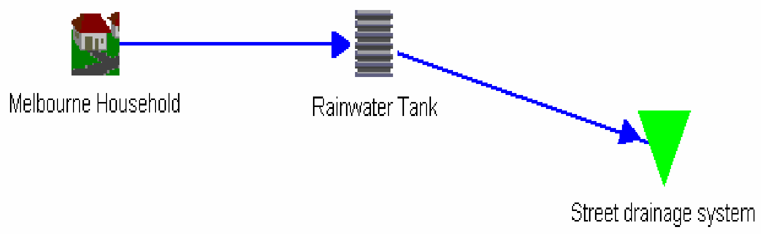

Figure 6.1: Schematic diagram of the MUSIC model for rainwater tanks

Figure 6.2 depicts the input values used in the analysis. The low flow and high flow by passes were kept at default values 0 and 0.003m^3/sec respectively. In addition, the surface area of the tank was also kept at the default value of 5m^2. As mentioned in preceding chapters that rainwater can be used effectively for non potable purposes such as: Toilet flushing (T), Garden use (G), Laundry use (L) or a combination of these. The demand values in previous chapters were used in analysing the stormwater quality and quantity improvements [Demand for toilet flushing= 16Lpcd; Demand for garden watering = 191L/day (restricted - 2 days a week for 6 months) and Demand for laundry use =39.7Lpcd]. Table 6.2 depicts the values for rainwater use for seven combinations of demand (Reuse properties in Fig 6.2). According to the MUSIC model manual either daily demand value or the monthly distribution of demand values have to be provided while carrying out the analysis. The monthly demand values were considered for the current analysis as there is no garden watering in winter months. Figure 6.3 depicts the percentage distribution of the monthly demand value for garden use. The monthly distribution for laundry and toilet demands were considered constant through out the year.

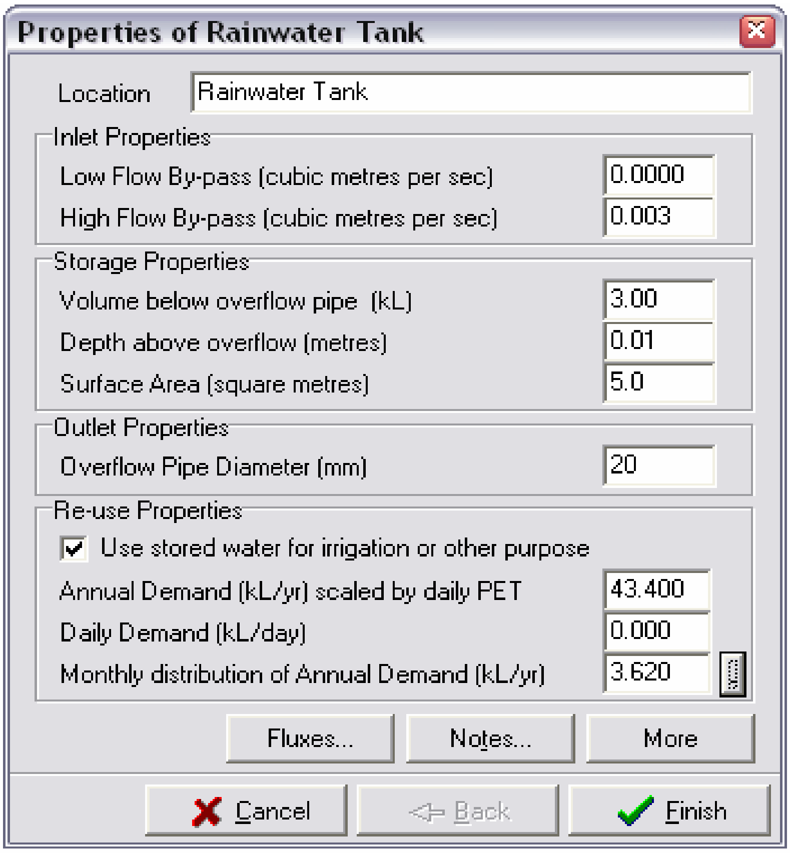

Figure 6.2: Input parameters for the flow component of rainwater tank

Table 6.2 Reuse properties for different demand types for a 3kL tank

Demand type	Annual demand (kL/year)	Monthly demand (kL/year)
T+G+L	68.9	5.74
T+L	61.0	5.08
T+G	25.3	2.10
G+L	51.3	4.28
T	17.5	1.46
G	7.8	1.3
L	43.4	3.61

** T - toilet flushing; G - garden watering; L - laundry use

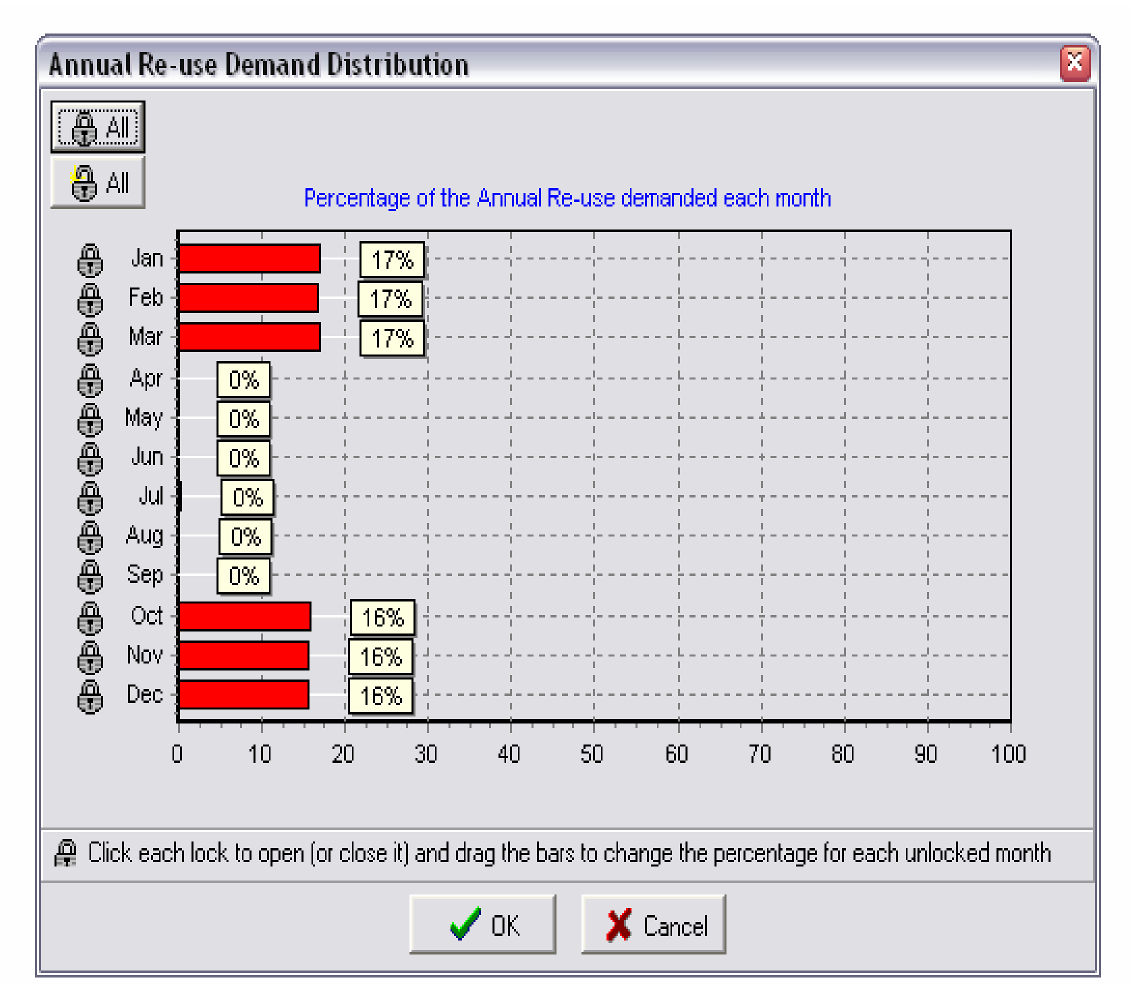

Figure 6.3 Annual distribution of rainwater use for garden watering

6.5.1 Calibration of the MUSIC model

The MUSIC model uses a tank model to generate surface runoff from pervious and impervious areas. Pollutants (TN, TP) from the surfaces will travel by attaching to sediments. Movement of sediments is directly related to the flow. As a result, it is very important to simulate the surface flow generated from the catchment (household property) accurately.

The surface runoff and residual from the rainwater tank estimated were generated using the MUSIC model and compared with the values simulated from water balance model. The MUSIC model has inbuilt rainfall data of the last 100 years in different parts of Australia to calculate runoff and pollutant fluxes associated with the proposed land use. In this study daily rainfall data for 10 years in Melbourne (April 1991 – November 2001) was used to determine the % reduction of Total Phosphorus (TP), Total Nitrogen (TN) and Total Suspended Solid (TSS) of stormwater by installing rainwater tanks. The schematic diagram of the tank model incorporated in to the MUSIC model is given in Figure 6.4.

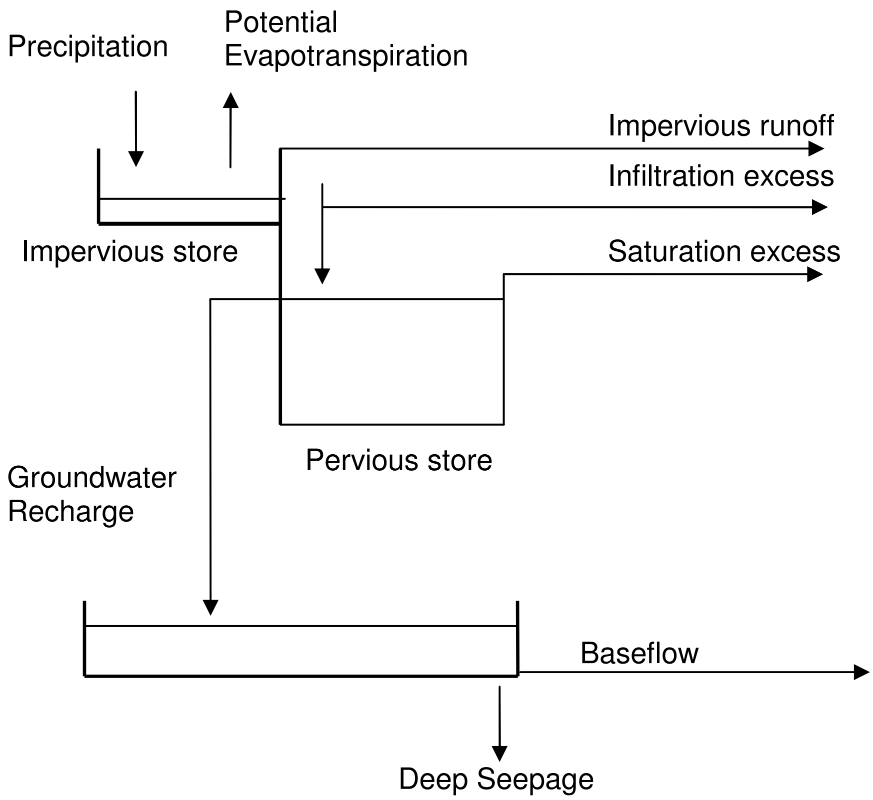

Figure 6.4 Conceptual daily rainfall-runoff model adopted for MUSIC

The Mean annual rainfall (MAR) for Hampton is 666mm which is equivalent to Melbourne's MAR of 660mm. To be consistent with the simulation, data from the Hampton station for the period from April 1991 to November 2001 was used in the water balance model simulation. The MUSIC model calculates the percentage reduction in stormwater runoff discharged into urban drains from the roof area by using Equation 6.1.

The roof area (A) connected to the rainwater tank was taken as the area of the catchment. As the roof surface is impervious the catchment area was considered as 100% impervious. By trial and error, the size of the impervious storage (threshold value of the rainfall) was changed until the surface runoff produced from the MUSIC model was equal to the roof runoff from the developed water balance model. In addition, the spill value from the water balance model was also compared with the equivalent residual load (amount of runoff into the urban drains) estimated from the MUSIC model. The surface runoff and residual load values were obtained when the rainfall threshold value was equal to 1.2 mm/day.

$$\% \text{Reduction in stormwater runoff} = \frac{\text{Surface runoff - residual load}}{\text{Surface runoff}} * 100\% \qquad (6.1)$$

The % reduction in stormwater runoff from the roof area was calculated by varying the tank sizes for different demands. Tables 6.3, 6.4 and 6.5 depict the percentage reduction in flow due to collecting stormwater in the rainwater tank and used in laundry, toilet and garden respectively. From the above Tables it can be observed that the % errors for toilet and laundry demands were less than 10%. However, the garden watering values were significantly different from the two methods used.

Table 6.3 Comparison of percentage reduction of stormwater from MUSIC model and water balance model (Laundry demand)

Tank size (kL)	**% Reduction of stormwater**		**%Error**
	MUSIC model	**Water Balance model**	
1	57.8	59.3	2.5%
3	73.4	74.6	1.6%
5	78.7	79.0	0.3%

Table 6.4 Comparison of percentage reduction of stormwater from MUSIC model and water balance model (Toilet demand)

Tank size (kL)	**% Reduction of stormwater**		**%Error**
	MUSIC model	**Water Balance model**	
1	34.2	33.3	2.7%
3	37.7	34.7	7.9%
5	37.9	35.1	7.3%

Table 6.5 Comparison of percentage reduction of stormwater from MUSIC model and water balance model (Garden demand)

Tank size (kL)	% Reduction of stormwater		%Error
	MUSIC model	Water Balance model	
1	16.7	10.7	56.8%
3	16.9	14.2	19.0%
5	17.0	15.0	13.0%

6.6 Percentage reduction of Flow, TSS, TN and TP

As mentioned earlier, the results discussed in this chapter were carried out for a typical residential household (3 people) of Melbourne. Different scenarios with 7 different combinations of demand were used to compute the percentage reduction of flow, TSS, TN and TP. Same three scenarios were used for demand management as Chapter 5. The scenarios tested were as follows:

Scenario 1: A 3 kL tank was used to determine Water quality improvements with different water demands. The roof area was considered to be 112.5 m^2 same as in Chapter 5. The MAR is 660mm/year.

Scenario 2: Demand for Toilet flushing, laundry use and Garden watering (same as in Chapter 5) with varying tank sizes of 1 kL to 5 kL. The roof area and MAR were assumed to be Similar to Scenario 1.

Scenario 3: A tank of 3 kL is installed with different demands and different roof areas. The roof area is assumed to be varying from 100 m^2 to 250 m^2. The MAR is taken as 660mm/year same as in Scenario 1.

Scenario 1

As discussed earlier, the analysis of Scenario 1 was carried out by considering the roof area of 112.5m^2 for a 3kL tank. Seven different combinations of demand were considered in the analysis to identify the % reduction in stormwater runoff and water quality parameters if rainwater is used for different non-potable use. Table 6.6 depicts the % reduction flow volume and % reduction of TSS, TP and TN for the 7 different combinations of demand types for a 3kL tank. From the above stated table it is evident that % reduction in flow varies with the type of demand. It could be as high as 75% if the rainwater was used for all three demand types i.e. toilet flushing, laundry use and garden watering.

As expected, if the rainwater is used only for garden watering the % reduction of stormwater that is flowing into urban streams is the lowest. It is obvious that if the usage of rainwater increases, the amount of water moving to street drainage system will reduce.

The % reduction of TSS varies from 92% to 97% with the demand for rainwater. However, there is a considerable variation in % reduction of TP and TN with the demand for rainwater.

Table 6.6: Reduction efficiency of peak flow, TSS, TN and TP by using a 3 kL rainwater tank for different demand types

Demand type	**Flow (%)**	**TSS (%)**	**TP (%)**	**TN (%)**
T+G+L	75.1	96.9	90.1	80.7
T+L	71.7	96.7	89.3	79.0
T+G	41.2	94.2	79.3	59.7
G+L	66.9	96.3	87.7	75.9
T	29.0	93.3	75.4	52.8
G	13.0	92.2	70.4	44.4
L	61.7	95.9	86.0	72.4

** T = Toilet flushing, G= Garden use and L = Laundry demand

Scenario 2

The analysis in Scenario 2 was carried out for constant roof area (112.5m^2) and demand (Toilet, garden and laundry). However, tank sizes were varied from 1kL to 5kL to observe the impact on reduction of flow, TSS, TP and TN due to variation in tank sizes. Figure 6.5 depicts the variation of reduction in flow volume, TSS, TP and TN due to variation in tank sizes.

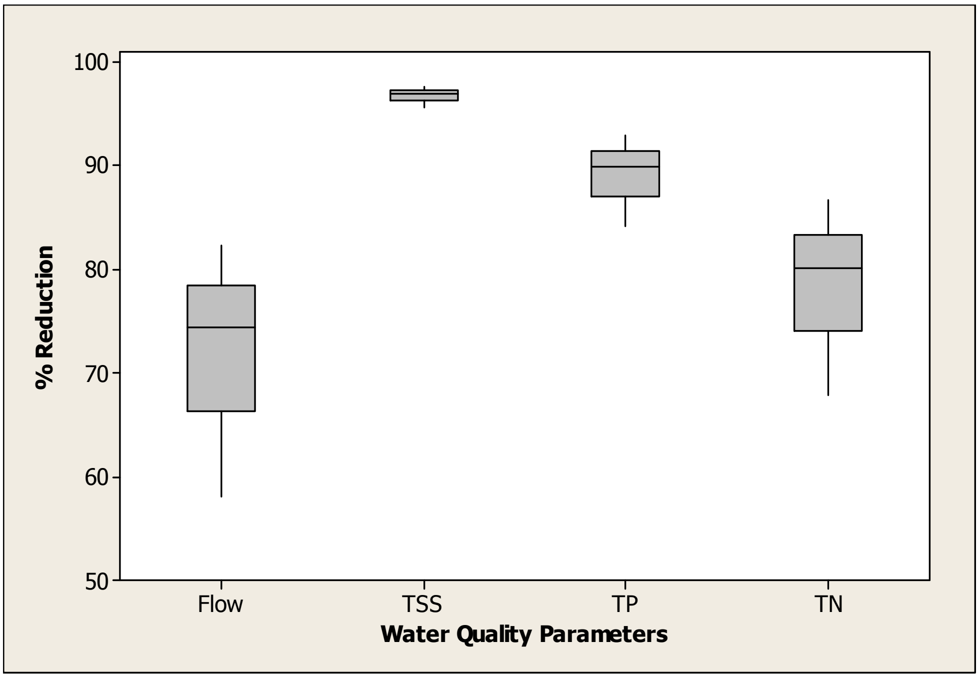

Figure 6.5 Percentage reduction efficiency of flow, TSS, TP and TN due to variation of tank sizes from 1kL to 5kL (1 kL tank shows the lower limit of the bar chart)

The Figure illustrates that there will be considerable variation of % reduction in flow due to variation in tank sizes. For example, the % reduction of flow can vary from 58% to 82% if the tank size varies from 1kL to 5kL. Similar to Scenario 1, the % reduction of TSS is high irrespective of tank sizes. However, % reduction of TP depends on the size of the tank. For instance, % reduction of TP varies from 84% to 93% when the tank size varies from 1kL to 5kL. However, this variation is distinctly visible in case of % reduction of TN. The % reduction of TN will increase by 19% (68% - 87%) if the tank size changes from 1kL to 5kL.

In summary, % reduction of flow, TP and TN vary considerably due to variation in tank size (Scenario 2) and demand (Scenario 1). However, for the % reduction of TSS this variation is minimal.

Scenario 3

In this Scenario it was assumed that tank size would be kept constant at 3 kL. It was also assumed that the surface area of the tank was 5m^2. However, roof area was assumed to vary from 100m^2 to 250m^2. In this scenario the demand of Toilet Flushing, Garden watering and Laundry use were considered to find out the % reduction of flow, TSS, TN and TP. Figure 6.6 depicts the % reduction of flow, TSS, TN and TP for roof areas of 250m^2, 200m^2, 150m^2 and 100m^2 respectively.

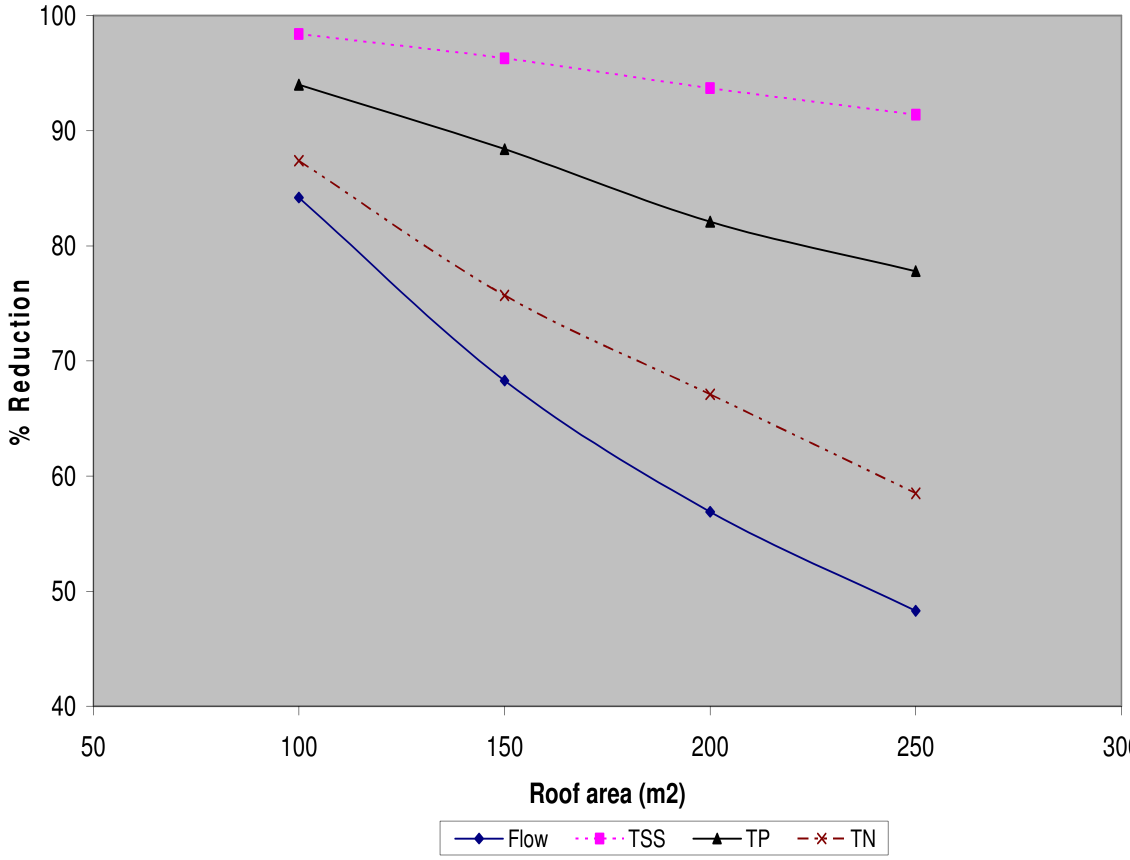

Figure 6.6 Reduction efficiency of flow, TSS, TP and TN due to variation of roof area for a 3kL tank (Toilet flushing, Garden watering and Laundry use)

The figure shows that with increase of roof areas the percentage reduction decreases. With the increase of roof area the amount of source load (input) increases. Although, the demand for rainwater is the same, the usage could also increase depending on the availability of rainwater in the tank. This indicates that due to increase of roof area the supply of rainwater into the tank is more than the demand. Hence, the reduction efficiency does not increase in line with the same proportion.

6.7 Stormwater mitigation in Greater Melbourne by using rainwater tanks

WSUD (2006) reported that "Total Watermark 2004" invited residents; business and the visiting community of the City of Melbourne to save water, improve water quality and protect the waterways. According to the WSUD Guidelines the main objective of above initiatives were to manage the demand (minimise water consumption), maximise stormwater reuse and treat stormwater runoff to meet the guidelines. This will facilitate the reduction of pollutant loads to the stormwater systems and Port Philip Bay.

According to the “Stormwater Management Best Practices Guidelines” the reduction targets that could be achieved by 2020 are:

- 80% reduction of total suspended solids (TSS)
- 45% reduction of total phosphorous (TP)
- 45% reduction of total nitrogen (TN) and
- 70% reduction in litter entering stormwater from the site.

As reported in Chapter 5, Water Services Association in Australia WSAA (2006) revealed the information on the number of properties in three retail company zones in the Greater Melbourne area. (Table 5.1).

Total number of properties in Melbourne

= YVW (593,596) +SEW (553,941) +CWW (284,612)

= 1,432,149

It was decided to hypothetically estimate the amount of water quality improvement (Flow, TSS, TP and TN) if all the houses in Melbourne installed rainwater tanks.

It was assumed in Chapter 5 that 50% of the rainwater tanks in Greater Melbourne were connected to roof size of 100m^2, 25% to roof sizes with 50m^2 and the remaining 25% were connected to roof sizes of 200m^2. Same proportions of tank sizes were assumed to determine the water quality parameters as well. Hence, the effective roof area for the Greater Melbourne area is 112.5m^2.

If every household in Greater Melbourne is connected with a 112.5m^2 roof, total roof area in Melbourne is equivalent to = 1,432,149*112.5 = 161.1km^2

Total area of Melbourne = 8,806km^2 (Wikipedia 2008)

By using a 3kL tank which is connected with a 112.5m^2 roof for toilet, garden and laundry demand the % reduction efficiency of flow volume, TSS, TP and TN for a 3 kL tank are 75.1%, 96.9%, 90.1% and 80.7% respectively (Table 6.6).

6.7.1 Reduction in Load

From the MUSIC model, for a 3 kL tank which is connected to a 112.5m^2 roof for toilet, garden and laundry demand, the computed impact on source load, residual load and reduced load are as follows:

Flow Volume

Source Load (roof runoff)	= 0.0065 ML/year
Residual Load (spill)	= 0.00167 ML/year
Reduced load	= 0.004202 ML/year

Hence, in Melbourne reduced load of Flow volume with a 112.5 m^2 roof

= 0.00483 x1432149

= 6918 ML/year

In addition, reduction in stormwater runoff volume if all houses install rainwater tanks

$$Percentage \quad R_{M}(F) = \frac{161.1}{8806} \times 75.1\%$$

= 1.38%

Total Suspended Solid (TSS)

Source Load (Roof Runoff)	= 13.9 kg/year
Residual Load (Spill)	= 0.475 kg/year
Reduced load	= 13.425 kg/year

Hence, in Melbourne reduced load of TSS with a 112.5m^2 roof

= 13.425 *1432149

= 1.92*10^7kg/year

Reduction in percentage of TSS if all houses install rainwater tanks

$$Percentage \quad R_{M}(TSS) = \frac{161.1}{8806} \times 96.9\%$$

= 1.94%

Total Phosphorus (TP)

Source Load (Roof Runoff)	= 0.0277 kg/year
Residual Load (Spill)	= 0.00281 ML/year

Reduced load = 0.02489 ML/year

Hence, in Melbourne reduced load of TP with a 112.5 m^2 roof

= 0.02489 *1432149

= 35646 kg/year

Reduction in percentage of TP if all houses install rainwater tanks

$$Percentage \quad R_{M\ (TP)} = \frac{161.1}{8806} \times 90.1\%$$

= 1.65%

Total Nitrogen (TN)

Source Load (Roof Runoff) = 0.177 kg/year

Residual Load (Spill) = 0.0338 kg/year

Reduced load = 0.1432 kg/year

Hence, in Melbourne reduced load of TN with a 112.5 m^2 roof

= 0.1432 x1432149

= $2.05*10^5$ kg/year

Reduction in percentage of TN if all houses install rainwater tanks

$$Percentage \quad R_{M\ (TN)} = \frac{161.1}{8806} \times 80.7\%$$

= 1.48%

From the above stated information it can be observed that by using a 3kL rainwater tank connected with a 112.5m^2 roof (for toilet, garden and laundry demand) in every household of Melbourne it is possible to reduce 2.0% TSS, 1.7% TP and 1.5% TN. As a result, rainwater tanks can be used efficiently as a potential WSUD component to treat stormwater and assist to achieve the target set by “Total Watermark 2004”.

6.8 Summary and conclusions

This chapter summarized the work carried out by other researchers related to water quality in rainwater tanks. The quality of rainwater collected from the roof and stored in the rainwater tanks depend considerably on the maintenance of the tank. Beside this, the type and design of tanks and removal of the first flush can improve the quality of stored rainwater in the tank. Hence, it is important to carefully select the appropriate type and design of the rainwater tank.

Different water borne diseases may occur from the use of untreated tank water due to faecal contamination caused by birds and animal droppings. On top of this, contamination with roofing paint and materials can also deteriorate the quality of rainwater. The quality of rainwater can be improved by using quality improvement devices and proper management of the tank and roof surface. For instance, the use of first flush devices will dramatically improve water quality. Based on the previous research it was found that the samples taken from the tank fitted with the first flush diverter consistently yielded low to zero total coliforms and E coli. As a result, it should be mandatory to install at least a first flush device to safeguard the roof collected rainwater against contamination, if the water is considered to be used for potable purposes.

The study analysed the effectiveness of rainwater tanks to reduce the stormwater runoff volume and quality that will flow to urban drains. The study observed that there was a considerable impact on water quality improvements due to the variation in demand of the stored water in the tank. This variation of % reduction was distinctly visible for flow (13% - 75%) and TN (72% – 80%). Irrespective of tank sizes and demand, the % reduction in TSS is more than 90%.

According to the “Stormwater Management Best Practices Guidelines” the aspirational reduction targets that could be achieved by 2020 are 80% reduction of total suspended solids (TSS), 45% reduction of total phosphorous (TP), 45% reduction of total nitrogen (TN) and, 70% reduction in litter entering stormwater from any site. By using the MUSIC model it was found that if every household in the Greater Melbourne area is connected to a 3kL tank (connected with a 112.5m^2 roof toilet, garden and laundry demand) 1.4% stormwater runoff, 1.9% TSS, 1.7% TP and 1.5% TN will be prevented from entering the urban drainage system. Although these percentage reductions are minimal in comparison with the above stated target, rainwater tanks can be considered as an auxiliary feature of WSUD component provided at the household level along side widely used sedimentation basins, wetlands, ponds, swales, sand filters and bioretention basins.

In addition to quality of the water stored in the tank, the cost of the tank (i.e. initial investment) is also a factor when taking a decision whether to or not install a rainwater tank. The cost of the rainwater tank, the value of water saved by using the tank and related issues are discussed in detail in Chapter 7.

Chapter 7

Investment Evaluation of Rainwater Tanks

The effectiveness of rainwater tanks to supplement reticulated water supply was in Chapter 5. Due to the on going drought and water restrictions people are looking for alternative supply to meet water demand. There is also apprehension amongst Melbournians regarding the tightening of restrictions to Stage 4 in the coming future if the drought situation continues for a longer period. The Government has also announced that the cost of water will increase considerably in by 2013. When deciding whether or not to invest, one of the important factors governing the decision is the capital cost (initial investment). As a result, it is important to investigate further the costs associated with installing a domestic rainwater tank. Although the total expenditure of installing the rainwater tank is borne by the tank user (and possibly the Government if the proponent is eligible for a rebate), the benefit of the tank is enjoyed not only by the tank users, but also the community.

The main objective of this chapter is to carry out a cost effectiveness analysis in order to estimate the payback period, cost effectiveness ratio and the levelized cost of installing a rainwater tank. The other objectives of this study are to determine the impact of inflation rate, interest rate and the period of analysis on the above stated parameters.

7.1 Background

The Victorian Government introduced the “Water Smart Gardens and Homes Rebate Scheme” which provides every household with an opportunity to conserve their water resources and save money (Department of Sustainability and Environment 2007). The Government has committed $10 million over four years to provide the means and an incentive for Victorians connected to a reticulated water supply to conserve future water resources. The Government has recognised the importance of plumbing the rainwater tank to the toilet and offered cash rebates for the installation of connected rainwater tanks.

Coombes (2002) illustrated that the use of rainwater tanks to supply outdoor and indoor demand would postpone the construction of some new water supply infrastructures for 34 years in the Lower Hunter region. In addition, the study explained that the installation of rainwater tanks in all new and developed dwellings could delay the requirement of constructing the next dam by 26 years. Collins and Davies (2004) stated that the construction of novel water supply headworks infrastructure could be delayed by up to 34 years due to popularity of rainwater tanks in the future.

Marsden Jacobs Associates (MJA 2007a) performed the cost-effectiveness analysis of rainwater tanks for 5 major cities (Brisbane, Sydney, Melbourne, Adelaide and Perth) of Australia. The study demonstrated that the levelized cost of rainwater tanks varied from $5.1 (Sydney) to $11.59 (Adelaide). However, the study did not consider the rebate scheme available for Melbourne which might further bring down the cost.

Grant and Hallmann (2003) performed life cycle assessment and costing of a 600 L and 2250 L domestic water tanks in the north-eastern suburbs of Melbourne. The 600 litre plastic tanks was used for watering the garden without installing a pump and the 2250L tank was used for garden watering and toilet flushing both. As such, the latter needed a pump. The study revealed that for the 600L tank the water savings was 15.5% where as for the 2250L (garden and toilet use) it was 54.9%. The pay back period was calculated to be over 30 years for both tanks.

Mitchell and Rahman (2006) performed the life cycle cost analysis of a 75kL rainwater tank for a commercial property in Sydney. It requires much more than 60 years (expected lifetime) to gain benefit from the rainwater tank if the present interest rate as well as mains water price persists. However, the above authors reported that if mains water price increases considerably the payback period will reduce dramatically. In addition, Eroksuz et al (2006) illustrated that a reasonable pay back period might be possible to achieve under some favourable conditions.

Rahman et al (2008) reported a computing tool which was used to carry out the benefit cost analysis for a multistorey residential building in Sydney. The authors carried out a number of analyses to calculate the pay back period for a 75 kL rainwater tank. The authors revealed that there are a number of parameters such as: roof area, discount rate, and water price and inflation rate that need to be considered when calculating the cost benefit ratio. The most favourable financial condition the study observed was a combination of 1600 m^2 roof area, 5% nominal discount rate, Aus$1.634/kL water price and inflation rate of 4.5% per annum for water price. The study revealed that the above stated parameters would provide a benefit cost ratio of 1.34. Rahman et al (2008) using large water tanks as on site detention basins in councils could be regarded as cost savings. A large roof and site area are more favourable than small tanks in terms of water savings and financial benefits.

Roebuck and Ashley (2006) developed a computer based modelling tool for rainwater harvesting. They reported that the current practice of rainwater tank analysis is incapable of determining the actual hydraulic efficiency as well as potential water savings from rainwater tanks. The study analysed the life cycle costing of a school building in the United Kingdom for a time period of 65 years. In addition, the study compared the results obtained by using their model with the results provided by the rainwater tank supplier. According to the tank supplier the pay back period was 10 years whilst according to Roebuck and Ashley (2006) it was 17 years. The reason for this discrepancy is that the rainwater tank supplier did not consider the impact of interest rate while carrying out the analysis. The above authors reported that it was important to consider the interest rate when calculating the payback periods.

Since the commencement of the Water Smart Gardens and the Homes Rebate Scheme in January 2003, there had been unprecedented reaction and willingness to take part and help save water (Smart water rebate). Around 150,000 rebates had been approved helping Victorians to save more than 1.2 billion litres of water a year, the study observed (SRWA 2007). Table 7-1 depicts the relationship between the amount of rebate ($), tank size and the expected use of the tank for the city of Greater Melbourne (SRWA 2007).

Table 7-1: Relationship between tank size, expected use and rebate amount for Melbourne (SRWA 2007)

Rebate Scheme	**Tank size (kL)**	**Expected use**	**Rebate amount($)**
1	≥0.6	Random use	150
2	0.6-1.999	Toilet flushing	150
3	2-4.999	Toilet flushing or Laundry use	500
4	≥5	Toilet flushing or Laundry use	900
5	≥5	Toilet flushing and Laundry use	1000

In addition, Victorian Government declared a $50 rebate for retrofitting of a dual flush toilet and $100 rebate for sustainable garden equipments which could be used in conjunction with rainwater tanks for attaining maximum water savings. It is possible to obtain approximately 30% of the initial investment due to this present rebate scheme if a potential tank user would like to install a rainwater tank equal to 5kL.

7.2 Price of reticulated water in Melbourne

The ever increasing water prices in urban reticulated water supply can act as a catalyst for encouraging rainwater harvesting in urban households alongside the above stated rebate scheme. The water prices of reticulated water supply Melbourne will rise by 14.8 per cent from July 2008 under a recommendation by the Victorian Government (Water Price 2007) per annum until 2013. The study reported that large families would pay up to $100 a year extra while singles in small houses or flats with medium gardens would pay about $45 more on water for a year. However, it is expected that due to the prolonged drought situation and the increase demand for water in Melbourne, the water prices will increase at a higher rate than the present inflation rate.

The price of reticulated supply in Melbourne varies with each water retailer (City West Water, Yarra Valley Water and South East Water). As a result, there is a variation in water price in different locations of Melbourne. Furthermore, water prices for domestic use depend on the volume of water (L/day) used (Tiered Price structure). Table 7.2 depicts the tiered price structure for a typical household in the Yarra Valley Water zone.

Table 7.2 Water prices of water retailers in Melbourne

Water retailers	**Water usage (L/day)**	**Volumetric Price ($/kL)**
Yarra valley water	0 - 440	0.81-0.82
	440-880	0.96
	>880	1.41-1.55

7.3 Cost effectiveness analysis of rain water tanks

As shown in Chapter 3, when one travels from west to north east of Melbourne there is a considerable variation in rainwater tank size to meet the same demand at an equal reliability. This variation can be as high as 7 times from Kinglake (North East) to Werribee (West) (Figure 3.9). Annual potable water savings (usage) also depend on the rainfall at the particular location (Figure 3.14). As a result, the cost of the tank along with the potable water savings will vary with the location. It was decided to use the rainfall data of three rainfall stations Werribee (MAR = 454mm), Berwick (MAR = 710mm) and Kinglake (MAR = 1050mm) to carry out the cost effectiveness analysis of the tanks.

As reported in previous chapters the rainwater will be used for toilet flushing, garden watering and laundry use. The demand values for toilet flushing, laundry use and garden watering were considered to be 16Lpcd, 39.7Lpcd and 191Lpcd respectively as reported in Chapter 3.

7.3.1 Components of costs when installing a rainwater tank

Cost of installing a rainwater tank can be divided into three parts. They are:

i. Capital investment

ii. Installation expenditure (Accessories Cost)

iii. Miscellaneous costs

Figure 7.1 depicts the layout of the different costs that can be associated with the total cost of installing a rainwater tank.

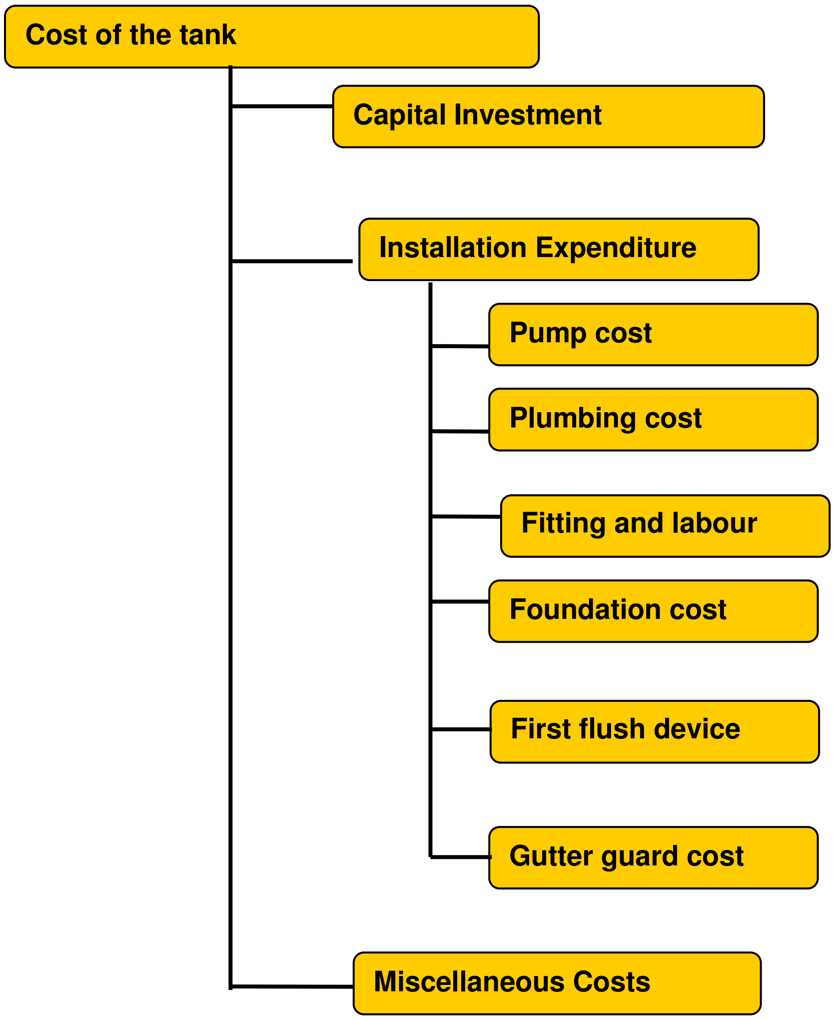

Figure 7-1: Components of the total cost of a rainwater tank

Capital Investment

Capital investment of a rainwater tank is the cost of the tank itself. Marsden Jacobs Associates [MJA, (2007)] reported that the price of the tank varied from $1300 to $5000 per tank for a domestic rainwater tank depending on size. However, the price of the rainwater tank depends on the shape, size and the material. In the current study a typical above ground round tank was considered for the analysis. Table 7.3 details the standard above ground round rainwater tank prices [Rainwater Tanks (2007) and Rain Harvesting (2007)].

Table 7.3**:** Rainwater tank prices [Rainwater Tanks (2007) and Rain Harvesting (2007)].

Tank size (kL)	Estimated price($)
0.5	350
1	460
1.5	500
2	600
2.5	650
3	680
3.5	715
4	750
4.5	825
5	900
5.5	950
6	1000
6.5	1110
7	1220
8	1375
9	1531
10	1686
11	1779
12	1872
13	1966
14	2059
15	2152
16	2245

Installation Expenditure (Accessories cost) (AC)

Once a rainwater tank is purchased there are additional costs involved in installing the rainwater tank. These costs vary a lot according to the tank user expectation, the area in which the tank will be installed (council guidelines) and user's affordability. In general, they are for the pump, plumbing, fitting and labor, foundation, acoustic cover, first flush device, gutter guard etc.

a. Pump cost

The typical cost of a pump varies from \$150-\$500 (Shopping Australia 2008). In this study, the cost of the pump (basic pump) was considered to be \$150. This also includes a pressure control or mains back-up device which automatically switches between rainwater and mains water when the tank is empty.

b. Plumbing cost

To be eligible for a rainwater tank rebate the tank must have an internal plumbing connection, for example to the laundry and/or toilet. Hence, it is an imperative to ensure proper plumbing connection. In this study the plumbing cost was considered as \$400 (Archetype Design 2007).

c. Fitting and labor cost

This cost depends on availability of labor, the day in which the work will be done (weekdays and weekends). In this study, it was considered that labor cost would be \$100.

d. Foundation cost

The concrete foundation cost of the rainwater tank depends on the size of the rainwater tank. Table 7.4 depicts the rough estimate of cost according to different sizes of rain water tanks [Rainwater tanks (2007)].

Table 7.4 Estimated cost of concrete base with different tank capacities [Rainwater Tanks (2007)]

Tank size (kL)	Estimated cost of concrete base (\$)
0-5	200
6-10	300
11-20	400
21-30	500

e. First flush device cost

These devices maintain the quality of the rainwater by diverting the first flush of rain away from the tank thus preventing contaminants from the roof entering the tank. The amount of first flush varies from 0.2 – 0.5 mm. In Chapter 3 the first 0.33 mm of rainfall from the daily rainfall was considered as the first flush. Table 7.5 indicates the typical price of different type of first flush devices available in the market [Rainwater tanks (2007)]. In this study it was decided that the tank is connected with roof water box first flush device.

Table 7.5 Prices of first flush devices [Rainwater tanks (2007)]

First flush device	Estimated market value($)
Pipe diameter	78
Roofwater box	600
Diversion tank	100

f. Gutter guard cost

Gutter guard cost varies with type and length. There are various types of gutter guards available in the market such as: square gutter, slotted gutter, og gutter and half round gutter (GRG 2007). In this study the very simple type of gutter guard i.e. square gutter was considered. Table 7.6 illustrates the costs of square gutter guards for different lengths. In this study it was considered that the length of gutter guard was 12m.

Table 7.6: Costs of square gutter guards for different lengths (GRG 2007)

Gutter length (m)	Estimated market price ($)
4.5	8
6	16
12	70
18	155
30	288

Miscellaneous Costs

This type of cost generally includes yearly operation and maintenance costs (OMC). It is normally anticipated that this cost will be very minimum. While doing the cost effectiveness analysis it was predicted that the typical OMC for Melbourne was 0.1$

(10cents) per kL of tank capacity as reported by MJA (2007b). The total OMC is computed using Equation 7.1.

OMC= 0.1*Tank capacity (kL)* Analysis of life time (Year), (7.1)

For example, for a 5 kL tank with an expected lifetime of 40 years the total operation and maintenance cost will be 20 dollar.

Present value of cost, PVC= TC+AC+OMC, (7.2)

From the above stated discussion it can be stated that the cost of a rainwater tank and the various accessories can vary based on the selected type and design. As reported earlier, a typical round above ground tank was considered for the analysis. Table 7.7 depict the cost of a typical 5 kL tank used in this analysis.

Table 7.7 Summary of different costs required to install a typical 5 kL round above ground tank

Type of cost	**Cost ($)**
Rainwater tank	900
Pump	150
Plumbing	400
Fitting and labour	100
Foundation	200
First flush	600
Gutter guard	70
Operation and maintenance	20
Total	2440

Figure 7.2 depicts the breakdown of different cost components when installing a rainwater tank. It is evident that the accessories cost of a tank is much more than that of capital cost.

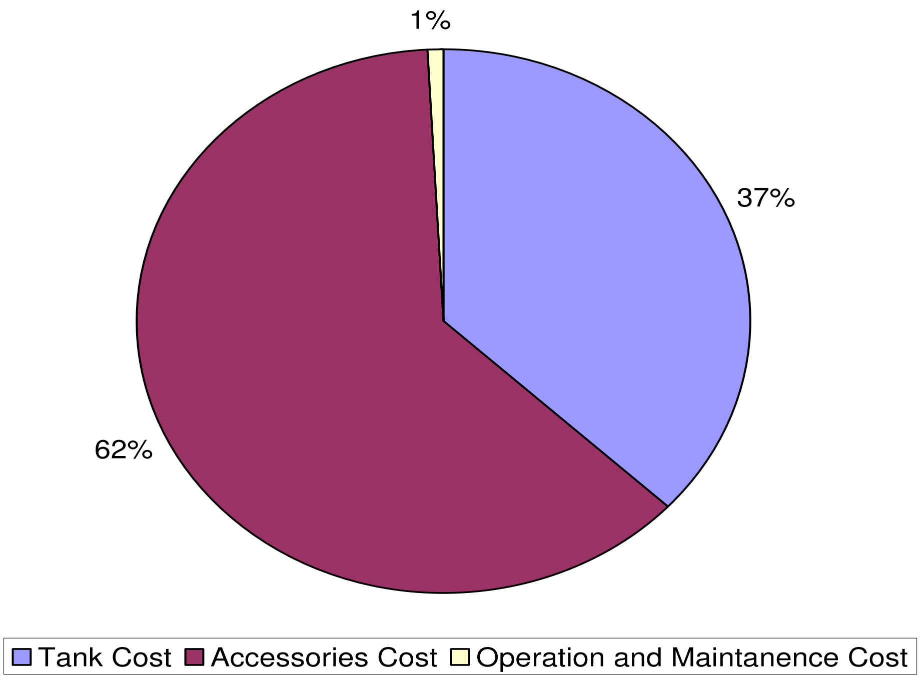

Figure 7.2 Breakdown of a typical 5 kL round above ground tank

7.3.2 Effectiveness of using rainwater tank (reticulated water savings, rainwater usage)

The savings of mains (potable) water supply ensures that the objective set by the government to reduce water consumption is achieved. The daily storage level of a typical water tank would depend on the volume of rainfall and the demand for rainwater. The water balance model was used to calculate the water storage levels from different tank sizes (Equation 3.3). The mean annual reticulated water savings (rainwater usage) was calculated using Equation 3.6. As shown in Table 7.8, there is considerable variation of annual water savings (RU) of rainwater when tank sizes vary from 1kL to 5 kL tanks in Berwick (MAR = 710mm), Werribee (MAR = 454 mm) and Kinglake (MAR = 1054 mm) respectively. Effectiveness of using a rainwater tank was calculated by considering the volume of reticulated water supply saved using the rainwater tank. However, price of mains water is not constant. Future value of water price was calculated using Equation 7.3. Future value of effectiveness of using rainwater tank was calculated using Equation 7.4. Net present value of effectiveness (E) of installing rainwater tank was calculated by using Equation 7.5.

$$FV_{WP} = WP * (1 + r)^n , \tag{7.3}$$

$$FV_E = FV_{WP} * RU \quad . \tag{7.4}$$

$$E = \sum_{t=o}^{n} \frac{FV_E}{(1+i)^n} \tag{7.5}$$

where,

WP = water price (per kL)

RU = Rainwater usage kL

r = Discount rate

i = Inflation rate

E = Net present value of effectiveness

n = Number of years of analysis

Table 7.8 Mean annual reticulated water savings (kL/year) from different tank sizes for a typical household (3 people) in Werribee, Berwick and Kinglake area (250m^2 roof area)

Demand	**Mean annual reticulated water savings (Rainwater usage) (kL/year)**								
	Werribee Tank size			**Berwick Tank size**			**Kinglake Tank size**		
	1 kL	**3 kL**	**5 kL**	**1 kL**	**3 kL**	**5 kL**	**1 kL**	**3 kL**	**5 kL**
T+G+L	30.6	44.8	50.1	38.8	53.4	58.2	47.3	61.0	64.2
T+G	17.9	22.3	23.4	18.3	22.6	23.8	20.2	23.6	24.0
T+L	30.8	43.9	48.6	38.7	51.0	54.7	46.6	56.8	58.2
G+L	28.2	38.8	42.3	33.0	42.5	45.7	38.5	46.9	48.3
T	15.7	16.5	16.7	15.6	16.8	17.0	16.7	16.8	16.9
G	5.4	7.3	7.7	5.3	7.1	7.5	6.0	6.9	6.9
L	27.9	36.5	38.7	32.1	38.9	40.7	37.0	41.4	41.6

Rebate scheme

As mentioned before, one of the benefits of installing a rainwater tank in Melbourne is the launch of a rebate scheme through which rebate up to $1000 can be obtained. Hence, present value of benefit can be calculated based on the tank size and the expected use of rainwater by using the rebate amount given in Table 7.1. Present value of benefit was calculated using Equation 7.6.

Present value of benefit (PVB) in \$ = Rebate amount (\$) (7.6)

7.4 Cost-effectiveness analysis

Cost-effectiveness analysis compares the costs and effectiveness of installing rainwater tanks. It is a relatively new concept in comparison with widely used cost benefit analysis. It is anticipated that for urban water supply systems, sustainable outcomes are promoted by identifying the least cost initiative which will facilitate economically sustainable means of service provision.

The use of rainwater tanks will reduce the usage of potable water from the reticulated water supply delivering societal benefit. A simple cost-effectiveness analysis of such an innovative and sustainable initiative will value the demand management impact on the traditional water supply of the installation of rainwater tanks.

Cost-effectiveness is always a ratio between cost and effectiveness. Equation 7.7 was used to compute cost-effectiveness ratio of rainwater tanks. In this study cost was calculated by subtracting benefit (possible rebate) from total cost (tank and related facilities cost). As mentioned earlier, effectiveness was computed by considering the total mains water savings due to the use of rainwater tank.

In this study, cost effectiveness analysis was carried out for a timeframe of 40, 30 and 20 years respectively. The cost-effectiveness ratio should be less than zero for an investment to be viable purely from an economic perspective.

$$\text{CER} = \frac{PVC - PVB}{E} \tag{7.7}$$

where,

CER = Cost - effectiveness ratio

E= Effectiveness of rainwater tank (Net present value of effectiveness)

By observing at the cost-effectiveness ratio value it is possible to judge whether the project will be financially beneficial after a certain period of time. For instance, if CER<=0 after 10 years, this means that the project will be financially beneficial after 10 years. Hence, CER value is considered as an indicator of financial viability of installing rainwater tanks as far as the potential customer is concerned.

7.4.1 Relationship of Payback period (PBP) of installing a rainwater tank

The payback period is the time taken to recover the initial investment i.e. the amount of time taken to break even on an investment. It is both conceptually simple and easy to calculate. In the current study, payback period is defined as the number of years required to get back the initial investment in the rainwater tank. It is important for a potential tank consumer to know the amount of time (payback period) required for the rainwater tank to be cost-effective in comparison to ongoing use of reticulated water supply.

There is a relationship between payback period and cost-effectiveness ratio. The payback period indicates the year from which the cost-effectiveness ratio will start to be less than zero. Payback period was calculated using Equation 7.8.

$$PBP = N_{CER \leq 0} , \tag{7.8}$$

where,

PBP = Payback period (year)

$N_{CER \leq 0}$ = Minimum Number of years required to obtain CER≤0

The results analysed in this chapter were carried out for the three rainfall stations which has low (Werribee MAR = 454 mm), medium (Berwick MAR= 710mm) and high (Kinglake MAR = 1054 mm) mean annual rainfall. A number of scenarios were used to compute the pay back period for a household of 3 people. In this analysis it was assumed that the number of people living in a house to be equal to 3 as the water used for toilet flushing and laundry use depend on number of occupants in the house. The scenarios tested were as follows:

Scenario 1: Different sizes of tanks were installed across the three stations. However, the roof area is considered to be constant (250 m^2) and the demand for rainwater is determined to be for toilet flushing, garden watering and laundry use. The mains water price was fixed at Aus$ 0.9/kL. The inflation rate was considered to be 4.2%. However, the discount rate of water was varied from 5% to 10%.

Scenario 2: Different sizes of tanks were installed across the three stations for meeting the rainwater demand of toilet flushing, garden watering and laundry use. The discount rate was constant at 5%. However, the inflation rate was varied from 3% to 5% and water price was fixed at Aus$0.9/kL.

Scenario 3: One constant tank size (5 kL) was installed across the three stations for meeting the demand of toilet, garden and laundry. The discount rate was constant at 5%. In addition, the inflation rate was constant at 5% and water price was varied from Aus$0.9/kL to $1.4/kL.

Scenario 1

It was assumed that the tank size was varying from 1kL - 5kL. The demand for this analysis was considered to be toilet flushing, laundry use and garden watering. Tables 7.9, 7.10 and 7.11 depict the relationship between payback periods for rainwater tanks of different sizes. The Tables below illustrate that with increase of tank sizes the pay back period is decreasing which is due to the fact that the maximum rebate peak at $1000 for installing a 5kL tank. In addition, in high rainfall areas it is possible to obtain payback period earlier in comparison with the low rainfall area as more potable water is saved.

One of the important factors of calculating the payback period was the price of mains water and the discount rate associated with this price. In this analysis it was considered that discount rate was varying from 5% to 10% with a fixed water price of $0.9/kL. The inflation rate was considered to be 4.2% which is the present inflation rate in Australia. It can be observed from the analysis that with increase of discount rate the payback period is reducing for a specific tank size. As a result, the most favourable economical condition for Scenario 1 is high rainfall (>1000 mm), area with a large tank size (5kL) when the discount rate is considered to be 10%. From the above Tables it can be stated that the payback period does not vary considerably with the discount rate. However, it varies considerably with the tank size impacting the initial investment required. Although, the initial investment is high when the tank size is big, the payback period is shorter.

Scenario 2

Scenario 2 was carried out by varying the tank sizes from 1 kL- 5kL. Roof sizes as well as the demand for rainwater were same as in Scenario 1. The main difference from the Scenario 1 was that the discount rate was kept constant. Inflation rate was varied from 3% to 5%. Due to rapid increase in fuel price it is expected that inflation rate will also increase quickly in the near future. Figures 7.3, 7.4 and 7.5 depict the relationship between payback periods for different rainwater tank with the inflation rate for the three selected locations. The figures illustrate that with increase of inflation rate the payback period also increases. According to the graphs the payback period is as high as 46 years at a 5% inflation rate in the low rainfall areas. On the other hand, for high rainfall area (Kinglake) the payback period may vary from 24 to 30 years for a 1 kL tank depending on the inflation rate. Similar to the previous Scenario the payback period depends on the tank size more than the rate of change in the inflation rate.

Table 7.9 Payback periods (years) of rainwater tanks due to variation in Discount rate (Werribee)

Discount rate	**Tank Size (kL)**		
	1 kL	**3 kL**	**5 kL**
5%	49	36	28
7%	35	28	24
10%	27	22	19

Table 7.10 Payback periods (years) of rainwater tanks due to variation in Discount rate (Berwick)

Discount rate	**Tank Size (kL)**		
	1 kL	**3 kL**	**5 kL**
5%	33	25	19
7%	26	21	17
10%	21	17	15

Table 7.11 Payback periods of rainwater tanks due to variation in discount rate (Kinglake)

Discount rate	**Tank Size (kL)**		
	1 kL	**3 kL**	**5 kL**
5%	27	21	18
7%	23	19	16
10%	18	16	14

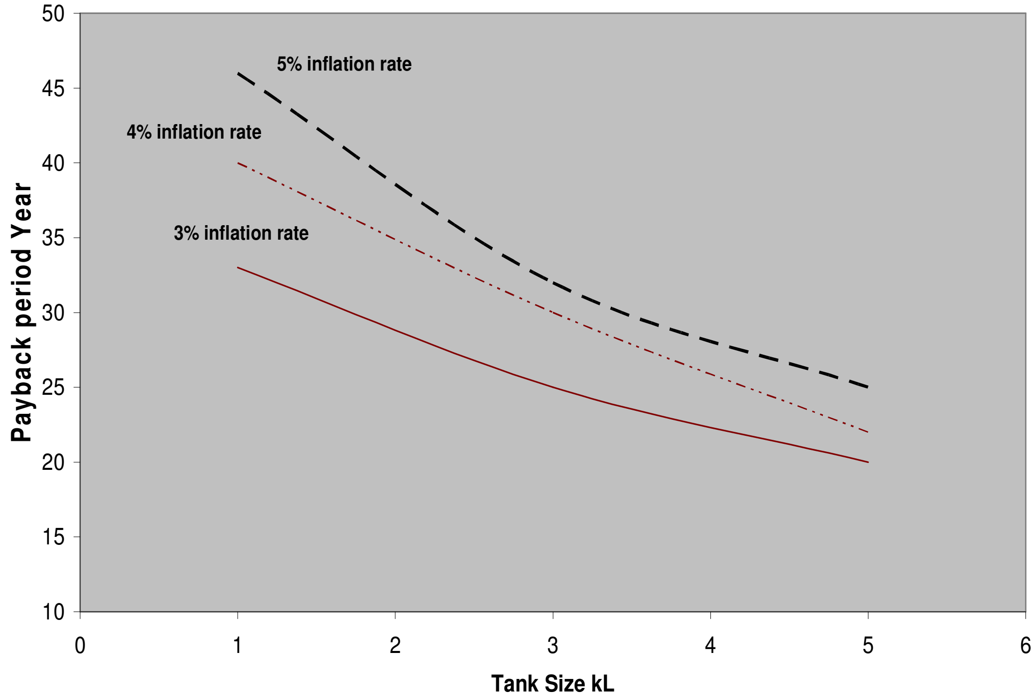

Figure 7.3 Payback period of rainwater for different tank sizes due to variation in inflation rate (Werribee)

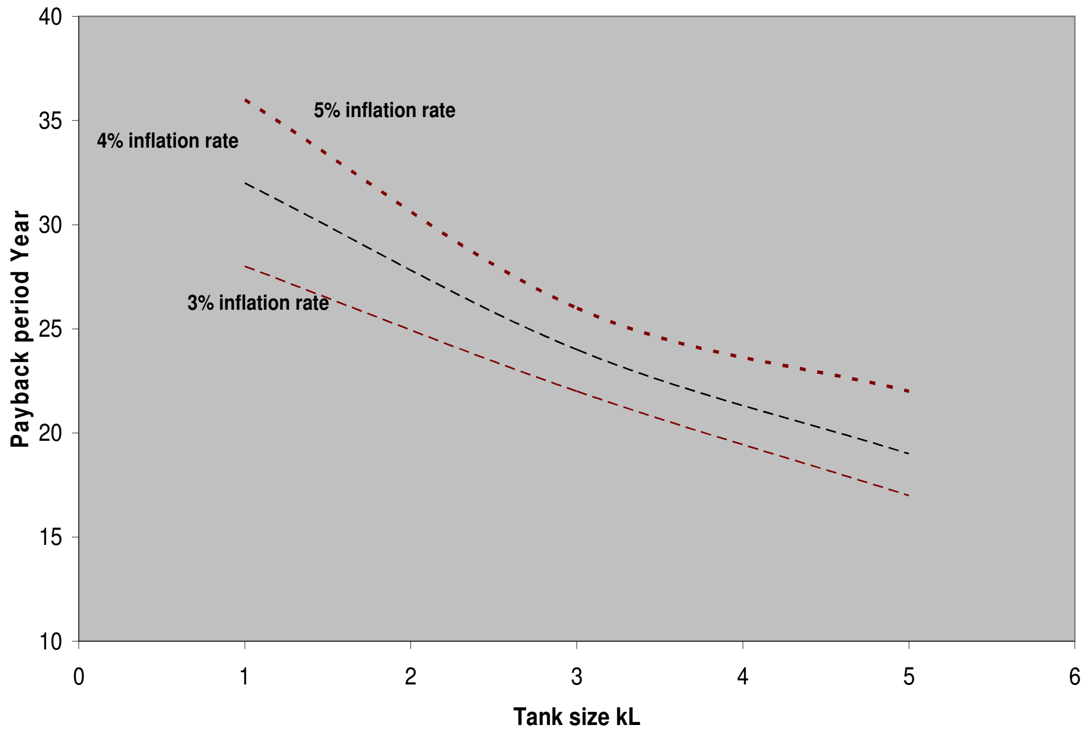

Figure 7.4 Payback period of rainwater for different tank sizes due to variation in inflation rate (Berwick)

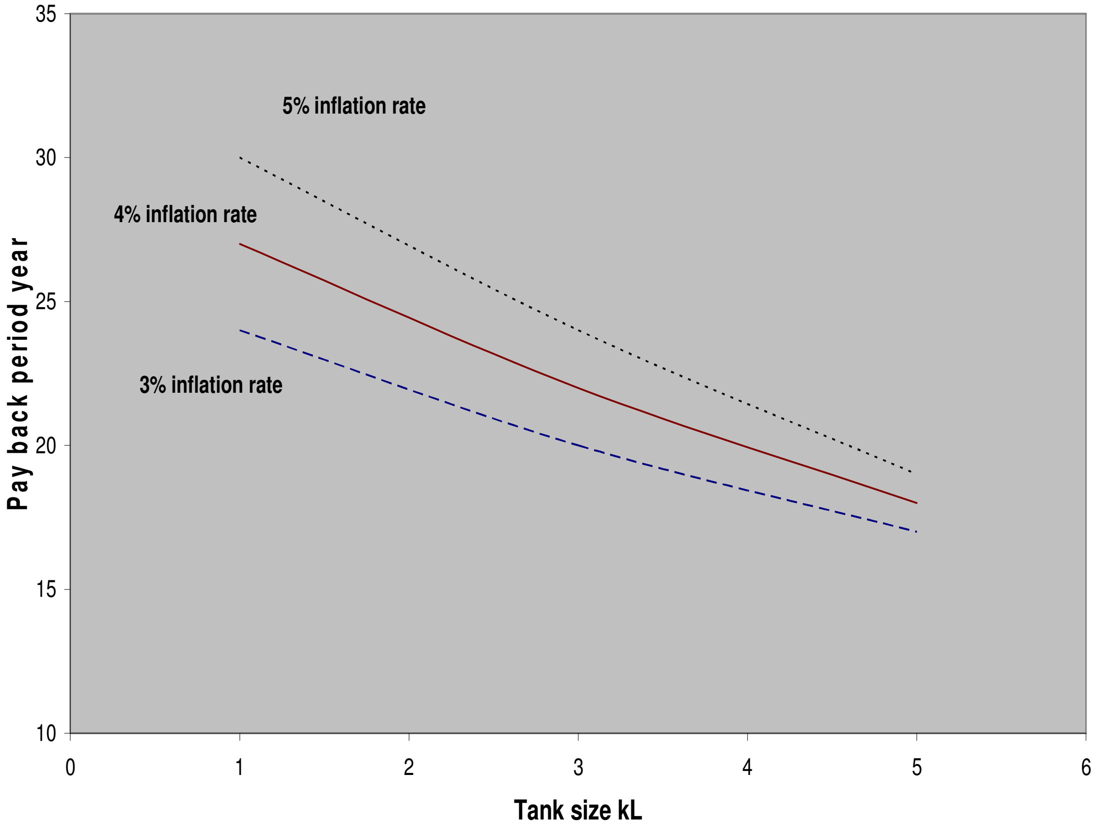

Figure 7.5 Payback period of rainwater for different tank sizes due to variation in inflation rate (Kinglake)

Scenario 3

Scenario 3 was carried out by keeping the tank size at 5 kL. Roof sizes as well as demand were assumed to be same as in Scenario 1 and 2. In addition, the inflation rate and discount rate were also considered as constant (5%). However, the mains water price was considered to vary from Aus$0.9/kL to $1.4/kL.

Figure 7.6 depicts the relationship between payback periods for a 5 kL rainwater tank due to the variation of mains water price. The figure indicates that payback period is significantly affected if the mains water price increases. The lowest payback period of 20 years was obtained in Kinglake if the mains water price increase to $1.4/kL. From the above Figure it can be observed that when the prices of mains water price increases, the difference in payback period is small with the change in MAR values (Location). For Werribee when the discount rate is 5% and inflation is also 5% the pay back period is 39 years for a 5kL rainwater tank (Table 7.9). It indicates that for this Scenario 3 there will be real savings in Werribee from rainwater use from 40th year onwards if the present water price persists up to that time. For the other two stations i.e. Berwick and Kinglake the cost effectiveness ratio will start to be less than zero from 33rd and 25th years respectively.

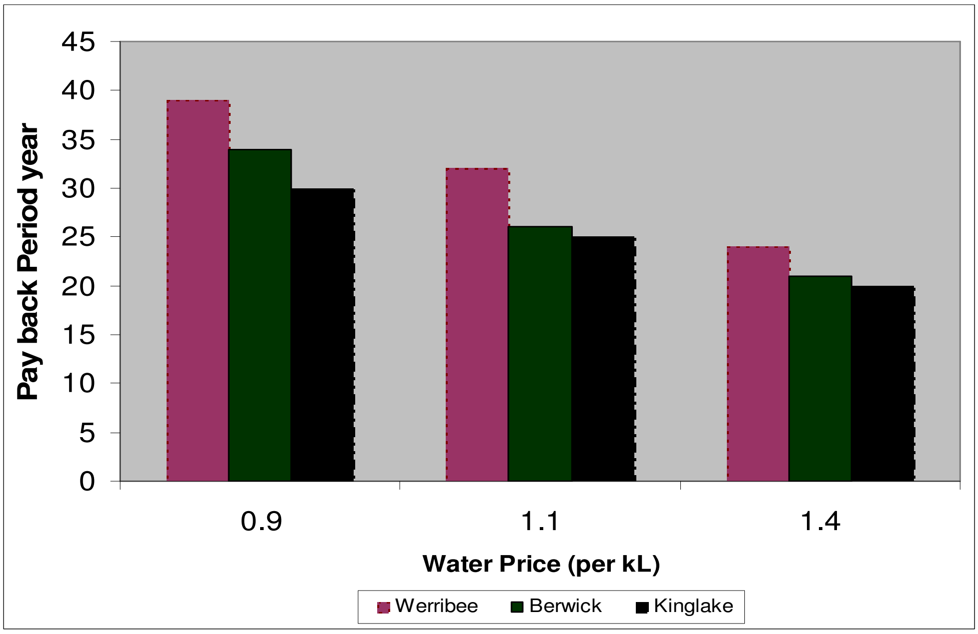

Figure 7.6 Payback period of rainwater for different tank sizes due to variation in mains water price for three different stations (Werribee, Berwick and Kinglake)

7.5 Levelized cost

The present value of the total cost of building and operating rainwater tank over its economic life, converted to equal annual payments is known as levelized cost. In general, it is important to know the levelized cost of the rainwater tank, with a view to comparing it with another traditional use (mains water supply) to have a clear understanding about the efficacy of tank use. The tank user can compare the mains water price with the above stated levelized cost to better understand the economic justification of the tank.

Marsden Jacobs Associates (MJA 2007b) showed the levelized cost of water from the desalination plant in Sydney and compared it with rainwater. The study reported that the levelized cost for water from the desalination plant in Sydney to be as high as $3.5. Nonetheless, due to inconsistent increases in the mains water price, it is difficult to have an accurate idea of what the future holds. The levelized cost of rainwater stored in a tank can be calculated by using Equation 7.7. Figures 7.7, 7.8 and 7.9 report the variation in levelized cost for a household of 3 people with discount rate of 5% for mains water price, constant inflation rate (4.2%) and a variation of tank sizes form1kL to 5kL. The cost of mains water price was considered to be 0.9/kL. In addition, the roof area and demand were assumed to be 250 m^2 and toilet, garden and laundry respectively. This analysis was carried out for the period of 40, 30 and 20 years respectively.

$$\text{Levelized cost, LC} = \frac{PVC - PVB}{RU * N}, \quad (7.7)$$

From the above Figures it can be stated that levelized cost of price of rainwater stored in a tank depend on the MAR of a particular location. The levelized cost varies from $1.54/kL (Werribee) to 1$/kL (Kinglake) for a 1 kL tank when the duration of project life is 40 years. In addition, the levelized cost decreases if the duration of the project increases. The levelized cost of rainwater almost doubles for Kinglake when the project duration reduces from 40 to 20 years.

It should be noted that the costs considered in the cost effectiveness analysis carried out in this chapter only considered the benefits to the consumer. In Chapter 6 it was shown that rainwater tanks significantly benefit stormwater management by reducing peak flows and trapping a large percentage of pollutants entry to the stormwater system from domestic properties. This too has significant benefit to the State depending on the penetration of tanks as it lowers stormwater management costs.

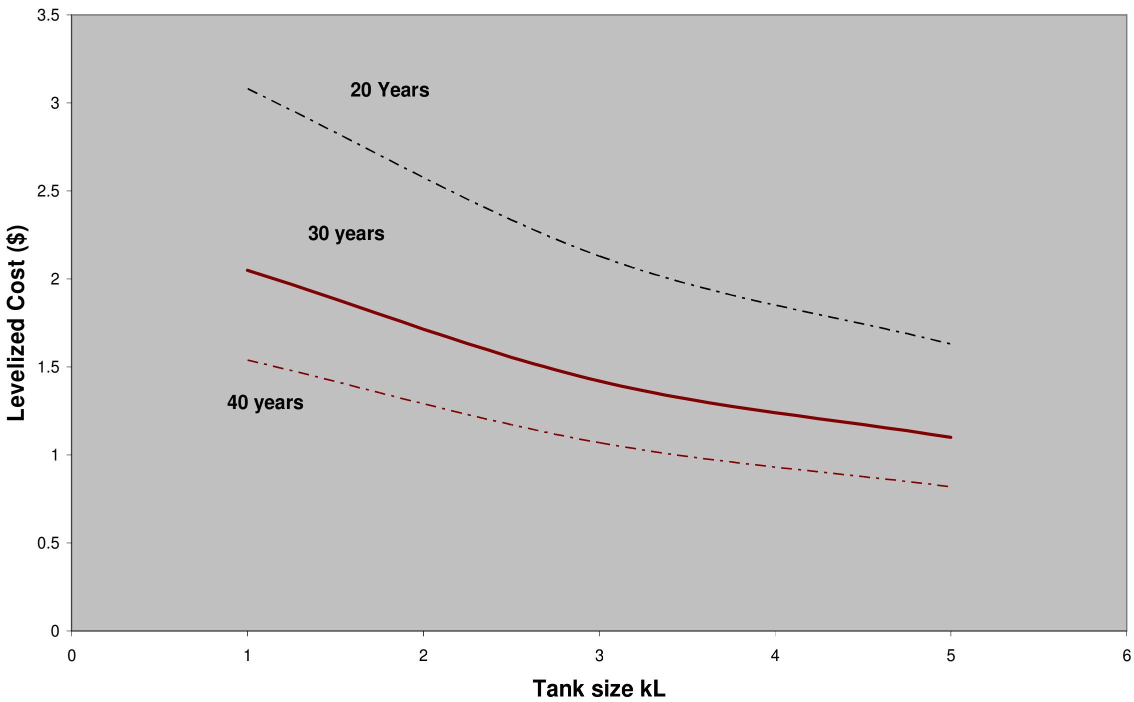

Figure 7.7 Levelized cost of rainwater for different tank sizes for the duration of 40 years, 30 years and 20 years respectively (Werribee)

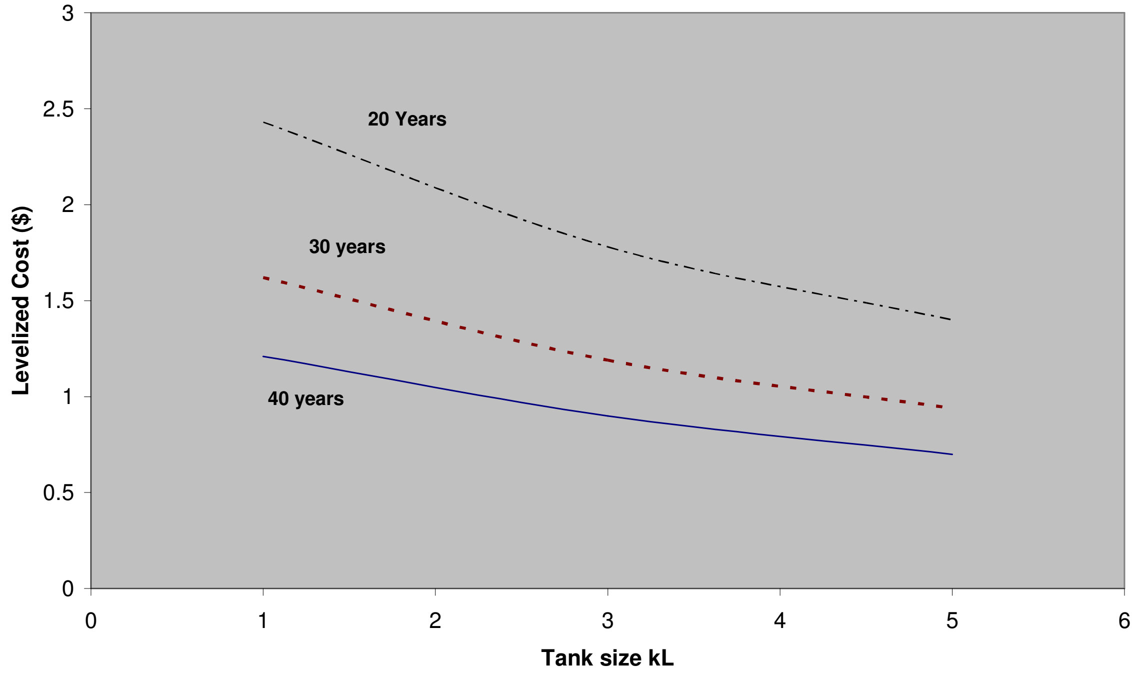

Figure 7.8 Levelized cost of rainwater for different tank sizes for the duration of 40 years, 30 years and 20 years respectively (Berwick)

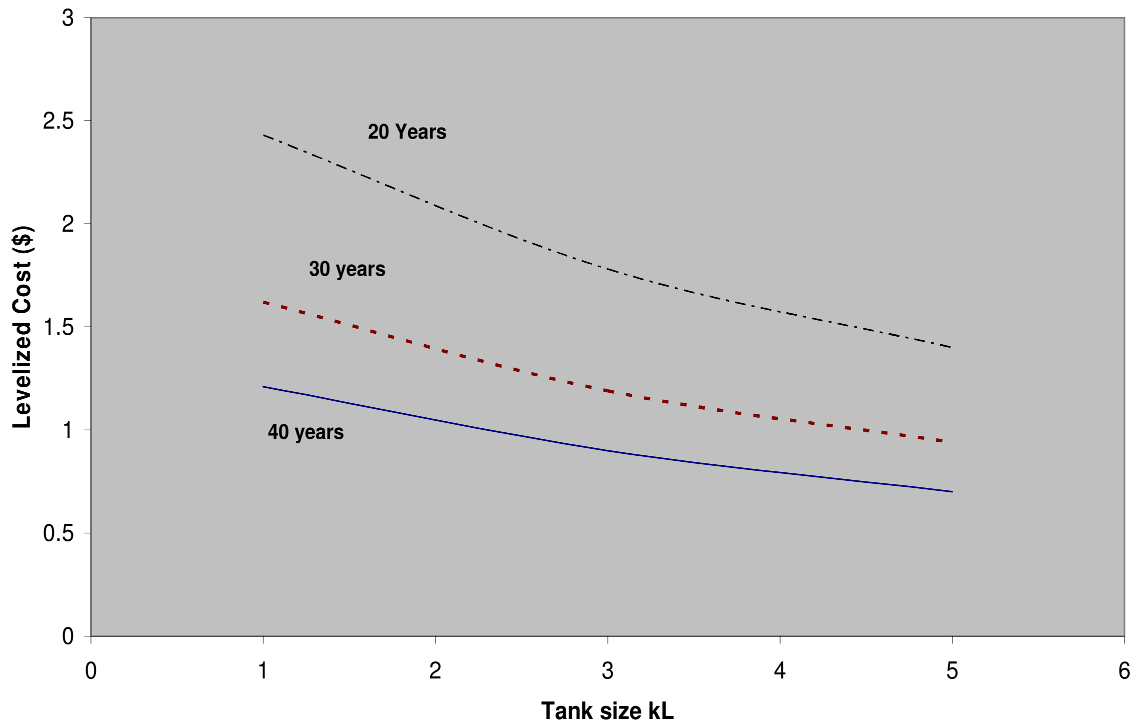

Figure 7.9 Levelized cost of rainwater for different tank sizes for the duration of 40 years, 30 years and 20 years respectively (Kinglake)

7.6 Summary and conclusions

The Chapter discusses about different costs involved while installing a tank. Capital cost and the accessories cost are the two major costs of installing a standard (5 kL) round above ground tank. Between these above two costs accessories cost contribute to 62% of the cost. The reason behind this is that in this study it was considered that the tank would be connected with protective treatment device such as: first flush and gutter guard which would ensure proper quality of water. However, the cost of the tank (capital cost) depends on the size of the tank. As a result, the percentage of cost that is illustrated earlier may vary due to change in tank size.

The Chapter illustrates the cost effectiveness analysis which was carried out to determine the effectiveness of rainwater tanks as a substitute of reticulated water supply in terms of cost. The Chapter describes the methodology which was developed to calculate cost effectiveness ratio, pay back period and levelized cost. One of the important considerations of selecting an optimum rainwater tank is the total expenditure incurred by the consumer. In addition, it is also important to have an appreciation about the levelized cost, pay back period and cost effectiveness ratio. The newly introduced rebate scheme by the Victorian Government generated extra interest among potential rainwater tank users. However, the economic benefit of rainwater tanks will continue to vary due to the rapid changes currently occurring for the mains water price, discount rate and inflation rate. Due to wide fluctuation in the world economy it is difficult to predict the future interest rate. As a result, in this study a range of reasonable discount rates (5 -10%) which is not too high or low is considered while carrying out the analysis.

The Victorian Government has announced that the price of water will double within the next 5 years. The Chapter illustrates several scenarios carried out to calculate payback period, cost-effectiveness ratio and levelized cost. The results discussed in the study revealed that cost-effectiveness ratio and payback period are the indicators of deciding the financial viability of installing rainwater tanks. From the scenarios analysed in this study it can be stated that it is possible to obtain pay back periods for rainwater harvesting under some financial condition. The results obtained from the above stated case studies showed that mains water price, discount rate and inflation rate are vital parameters which will have impact on the payback period of the rainwater tank. Ideally, a high mains water price, low inflation rate and high discount rate and high rainfall will ensure least payback period. It was observed that it was possible to obtain a payback period as low as 14 years for a 5kL tank in Kinglake (MAR = 1050mm) with a discount rate of around 10%.

In addition to the discount rate and inflation rate the tank sizes are also an important factor to determine the amount of cost that will be borne by a potential rainwater tank customer. The payback period does not vary considerably with the change of discount and inflation rate in comparison with the variation that can be observed due to tank size. This observation emphasizes the significance of selecting the optimum tank size to ensure maximum use of the rainwater at the most effective initial investment. It is quite obvious that the payback period is comparatively low for a large tank although the initial investment will be substantial in a high rainfall area as significant amount of potable water is saved.

To summarize, it can be stated that the optimization of the rainwater tank is also significant to minimize the capital expenditure of rainwater tank because variation in tank size will cause variation in cost. As a result, before selecting the optimum tank size a potential customer must also have an understanding budget that will be required to install the tank as well as appreciate the pay back period.

The main objective of this study is to optimize the rainwater tank size to minimize residential water consumption. In Chapter 3 it was shown that selection of appropriate tank size must be based on parameters i.e. roof area, demand, supply reliability and mean annual rainfall at a specific location if the tank size is to be optimized. Chapter 4 reported the methodology which was developed for establishing the generalized curve which will help a potential customer to select an optimum tank size based on the above stated parameters customised to his geographic location. Chapter 5 illustrated the benefit of optimum rainwater tank size because it is capable of substituting potable use of good quality reticulated water supply. Chapter 6 stated the importance of selection of optimum tank size because reduction efficiency of flow volume, TSS, TP and TN is dependent on tank size thus benefiting managing stormwater. Chapter 7 noted that the size of the tank is the most important parameter which influences the initial investment required to install a tank.

Chapter 8

Summary, Conclusions and Recommendations

8.1 Summary

Melbourne, the capital of the State of Victoria, Australia is renowned worldwide for good quality undisrupted potable water supply. Nevertheless, it is confronting growing water demand due to increasing population and economic development. Furthermore, persistent 12 year drought in Melbourne has dramatically reduced water stored forcing water restrictions.. Victorian Government has set an aspirational goal for reducing per capita water consumption by 15%, 25% and 30% by 2010, 2015 and 2020 respectively. Besides this, the Victorian Government has introduced stringent stage 3a water restriction to control the excessive use of potable water. If the present drought situation continues for another year Melburnians will have to face Stage 4 water restriction which totally prohibits external water use. A 14.8% per annum price hike to potable water supply was also announced by the Victorian Government from 1 July 2008. As dam storage levels continue to plunge, the use of alternative water sources such as rainwater is seen as the most viable source to save potable water and reduce the pressure on traditional reticulated water supply.

In Melbourne, legislation has been changed to make it possible to use rainwater for garden watering, toilet flushing, and laundry use and in hot water systems (non potable purposes). Substantial research has been carried out to verify the ability of rainwater tanks to supplement the potable reticulated supply. However, very few works has been carried out to determine the optimum rainwater tank size for domestic water conservation in Melbourne taking into account the highly variable rainfall pattern across the metropolis. It is important to ensure that there is enough water in the rainwater tank to meet the demand reliably as well as to closely examine the spillage and usage relationship for the desired reliability, before selecting the appropriate tank size for domestic use. The tank size depends on roof area, number of people in the household and the planned demand for rainwater, rainfall in the local area and the supply reliability required.

There is a significant variation in mean annual rainfall across Greater Melbourne. The spatial variability of rainfall across the Greater Melbourne area is from 450mm in the west to 1050 in north-east. The rainfall variability in Melbourne confirms that the ‘one size fits all' approach does not result in equitable outcomes for Melburnians as householders in the West of Melbourne will be constrained by the low annual rainfall environment.

The key features of this research are:

- Develop a methodology to estimate the optimal size of the rainwater tank considering the local rainfall in the area, number of occupants in the dwelling, demand for water and the reliability of supply required by the householder.
- Quantify the stormwater volume that could be harvested using rainwater tanks to minimise the pressure on the potable water supply provided using traditional pipes.
- Estimate the cost effectiveness ratio and the payback period of installing a rainwater tank.
- Analyse the efficacy of rainwater tanks to reduce stormwater runoff and improve the water quality of the stormwater that will otherwise flow into urban drains and receiving waters.

A water balance model was developed to determine the rainwater tank sizes in different locations in Melbourne based on some parameters such as: roof area, demand and supply reliability. The data base for the water balance model consisted of 20 stations distributed across the Greater Melbourne area. The model was applied to rainfall data from last 10 years which were the driest sequence of years in Melbourne. Seven different combinations of garden and in-house demand combinations for rainwater were considered in the analysis. The selection of the appropriate tank size varies with a number of parameters such as roof size, demand for water, roof area and supply reliability. As such, a number of charts which plots tank size with variables are required to be referred to in order to select the optimal rainwater tank size to meet the customer's needs.

Dimensionless analysis was used to reduce the number of independent parameters when determining the tank size. A reliability depended single curve was produced using dimensionless ratios to obtain the optimal tank size depending on annual rainfall, roof size and the anticipated demand. These curves are a useful, easy to use tool when a potential tank user wants to select the appropriate tank size depending of the available budget, cost of the tank and sustainable water use. This unique finding provides the opportunity to compute the tank selection process in the future, customising the tank size selection to reflect the needs of the consumer (type of demand to be met at predetermined consumer selected reliability), physical features such as roof area and local representative rainfall.

The water balance model was used to determine the amount of potable water that could be saved for a hypothetical scenario if all houses in Greater Melbourne installed rainwater tanks. In this analysis the whole Greater Melbourne were divided into three zones based on the three water retailers in Melbourne (Yarra Valley Water zone, South East Water Zone and City West Water Zone). The Theissen polygon method was used to calculate the MAR in each zone. A number of scenarios with different rainwater tank sizes, roof sizes and demand options were simulated to identify the amount of reticulated water that could be saved by the water authorities from now until 2012. Last three years (2004 to 2006) rainfall patterns were concatenated to generate synthetic sequences of rainfall for the next 5 years to test the efficacy of rainwater tanks in reducing potable demand. Results obtained for the 100% penetration of tanks could be proportionally adjusted to reflect a more realistic uptake of tanks and compute the corresponding potable water saved.

Although, in Melbourne it is permitted to use rainwater for non potable purposes which do not require good quality water, it is also important to assess the quality of rainwater stored in the tank. The quality of water and the possible reasons of contamination of rainwater stored in the tank were studied from literature to better appreciate issues impacting further in house use of rainwater. The MUSIC model was also used to determine the reduction in TSS, TP, TN and stormwater runoff volume that will otherwise flow into urban drains due to installation of rainwater tanks to quantify the stormwater management benefits derived by rainwater tanks..

Finally, the cost effectiveness of using rainwater for nonpotable domestic use in comparison with traditional reticulated water supply was analysed.

8.2 Conclusions

8.2.1 Rainfall variation across Greater Melbourne

- There is a considerable variation in mean annual rainfall (MAR) across Greater Melbourne area: (450mm in west to 1050 mm in north west).
- “One size fits all philosophy” is not applicable in Melbourne considering the spatial variability of MAR across Greater Melbourne. This is a tank size of 3kL capacity will not be able to provide consumers in the west with the same reliability of supply it provided a householder in the east. Hence the tank size has to be optimised to local needs taking into consideration the local hydrology.

8.2.2 Sizing of rainwater tanks

- The rainwater tank size depends on a number of parameters such as: roof area connected with the tank, supply reliability of water and expected demand (type and number of people in the household).
- To achieve the same supply reliability (90%) and meet a specific demand (toilet and garden use), the tank size required in the western side of Melbourne is as high as 7 times as that required in the north-east side.
- It was observed that there were three distinct rainfall patterns while providing a range of tank sizes. The ranges of MAR are:
    - MAR<550mm;
    - 550<MAR>850mm and
    - MAR >850mm
- Three dimensionless numbers were discovered during the study related to tank capacity (C m^3) annual water demand (D, m^3/year), roof area (A, m^2), mean annual rainfall (R, mm/year) and supply reliability (%). They are:

$$\pi_1 = \frac{C}{A^{\frac{3}{2}}} , \quad \pi_2 = \frac{D}{AR} \quad \text{and} \quad \pi_3 = \text{Reliability}$$

- Using dimensionless numbers a single generalized curve was successfully developed to estimate the rainwater tank size.
- In low rainfall areas (MAR < 550 mm/year) the rainwater can be used for toilet and garden use only with a reasonable reliability (85% and above).
- In high rainfall area (MAR > 850 mm/year) it is possible to meet any demand at a very high supply reliability.
- It is not practical to use rainwater for both indoor and outdoor domestic use in the western suburbs of Melbourne. The supply reliability is a low 40% with a large 5kL rainwater tank (connected to a 100m^2 roof area) if rainwater is being used for toilet flushing, garden watering and laundry use. That is 60% of the time a potential user would use tap water to meet the demand. This contrasts with the same 5kL tank whilst meeting a similar demand, delivering a 100% reliability supply in the North-East Melbourne.
- In areas with sufficient mean annual rainfall (700mm/year) the rainwater could be harvested effectively for domestic purposes to meet toilet, garden and laundry demand with a supply reliability of around 70%.

- It is possible to calculate the optimum tank size from the generalised curve for any area in Melbourne if the demand type, area of the roof and MAR of that local area is known.

8.2.3 Potable water savings by introducing rainwater tanks

- The MAR of the three Melbourne water retail company zones over the last 10 years was 798 mm, 709 mm and 486mm for Yarra Valley Water (YVW), South East Water (SEW) and City West Water (CWW) respectively. The MAR in CWW zone is about 30% lower than that of the YVW zone.
- Average annual potable water saving between 17% to 23% could be obtained if rainwater is used in the laundry together with toilet and/or garden and 3kL tanks are installed in all houses throughout the Greater Melbourne area with rainwater draining from an average roof size of 112.5m^2 (50% of the houses in the zone with 100m^2; 25% with 50m^2 and 25% with 200m^2).
- Water saving could be adjusted in proportion to above to reflect a less than 100% penetration of tanks.
- The total amount of water saved does not vary with average roof sizes assumed for houses if the demand for rainwater is small (garden watering or toilet flushing only).
- For a typical house, the total demand for rainwater is 12% of the reticulated supply if used for garden watering under no water restriction conditions.

8.2.4 Improvements to stormwater quality and quantity via rainwater tanks

- The quality of rainwater collected from roof stored in rainwater tanks depend considerably on the maintenance of the tank and the roof.
- Faecal contamination from birds and animal droppings can cause water borne diseases.
- It is important to install at least a first flush device to improve water quality in the tank.
- The impervious roof area connected with a tank is an important factor when determining the % reduction of flow, Total Suspended Solids (TSS), Total Nitrogen (TN) and Total Phosphorous (TP) otherwise will flow into the urban storms. With the increase in roof area from 100m^2 to 250m^2 the flow, TSS, TP and TN reduced by 5%, 15% and 26% respectively from an area equivalent to the roof area.
- The amount of reduction in runoff and improvements to water quality also depend on the demand (Toilet, garden and laundry to garden only) for stored rainwater in the tank.

8.2.5 Cost effectiveness analysis of a rainwater tank

- Capital cost and the accessories cost are the two major costs of installing a standard (5kL) above ground circular tank.
- The economic benefit of installing the rainwater tank will vary due to the rapid variation of mains water price, discount rate and inflation rate.
- It is possible to obtain a payback period of 14 years for a 5kL rainwater tank in the Kinglake (MAR = 1050mm) with a discount rate of 10% due to high utilisation of the tank.
- The payback period does not vary considerably with the change in discount rate and inflation rate in comparison with the variation in the tank size.
- Selection of optimum tank size is important (minimise spill) to ensure maximization of rainwater usage and minimization of initial investment.
- There is increasing evidence that consumers invest rainwater tanks to “feel good” about their contribution to save the environment.
- The other significant benefit that was not considered in this study was the effectiveness of rainwater tanks to minimize stormwater management cost.

8.3 Recommendations

- The optimal sizes of a rainwater tank should be determined after considering the geographic location in Melbourne, daily rainfall, roof size, intended use of rainwater and the supply reliability desired.
- The optimal size of the tank should be based on spillage and usage along with supply reliability. The optimal tank should minimize spillage and maximize usage.
- The generalized curve derived during the study can be used to select the optimum tank size for residential use based on the roof area, demand, MAR of a location and supply reliability.
- The developed methodology and the dimensionless curve concept can be applied to any area in Australia. This also provides an opportunity to computerise the methodology and facilitates the development of a web based technology to promote customized tank selection.
- More information is needed on the quality of collected rainwater in the urban Australian context.

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Appendix A

Relationship Between Rainwater Tank Capacity, Demand (D), Roof Area (A) Mean Annual Rainfall (MAR) In Different Locations Of Greater Melbourne

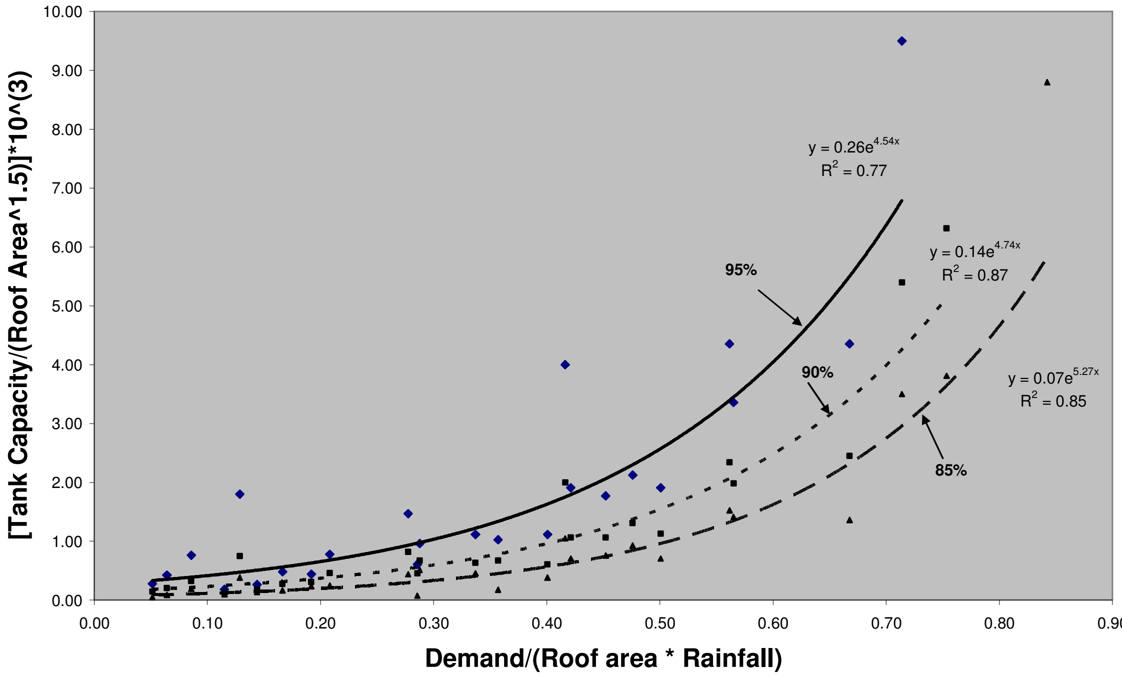

Figure A 1 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Arthur Creek)

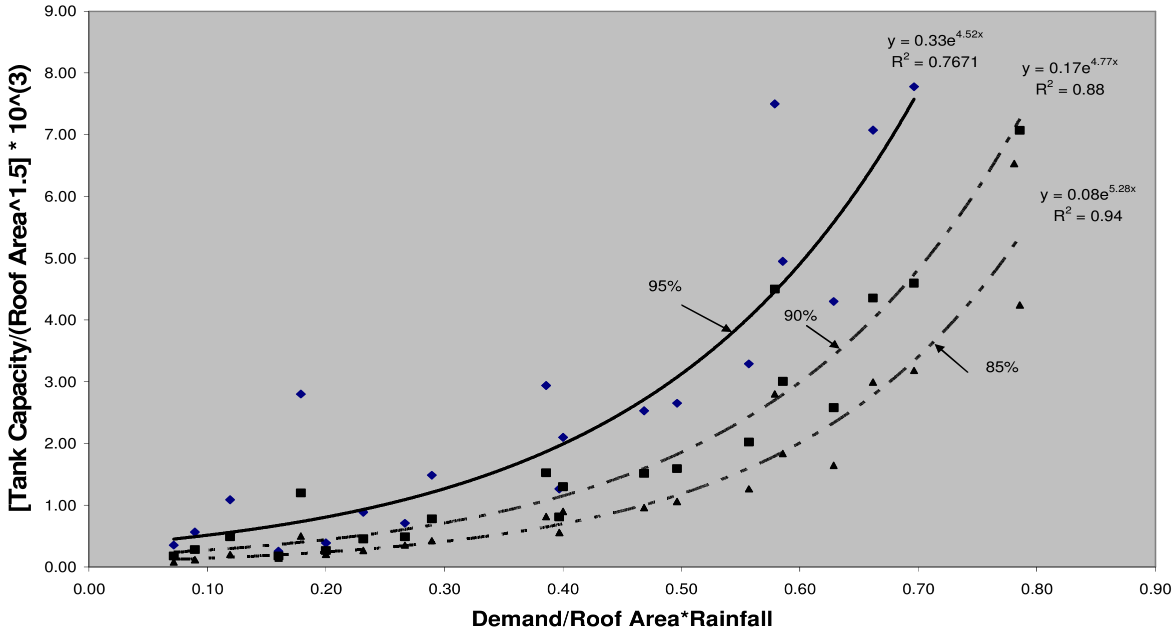

Figure A 2 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Rockbank)

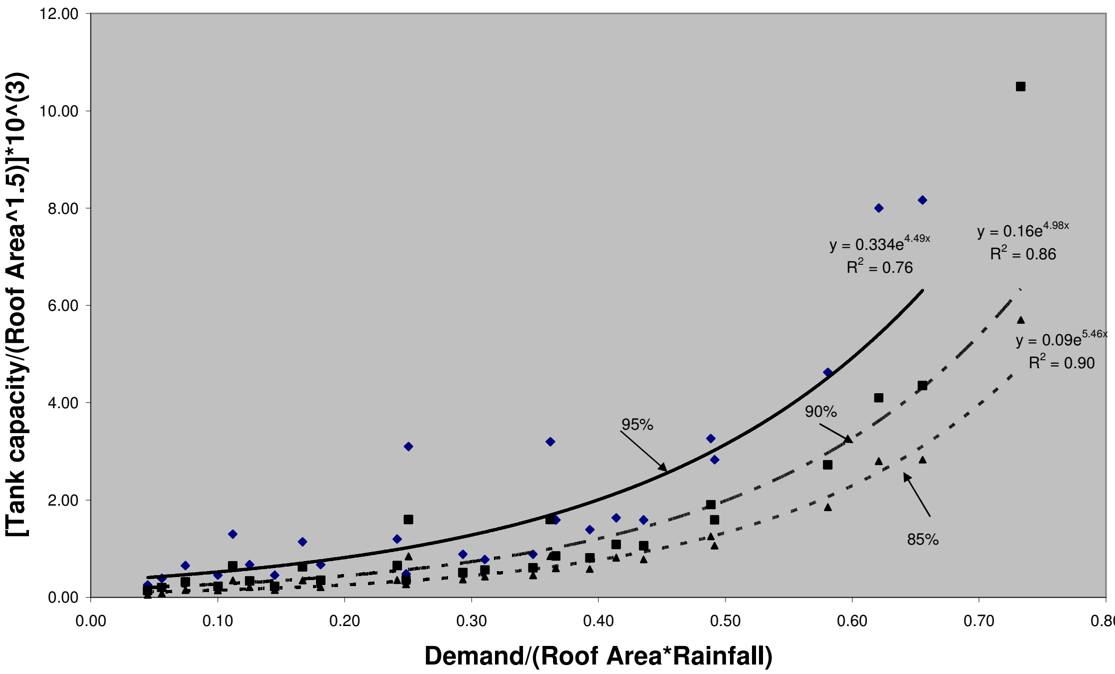

Figure A 3 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Sandringham)

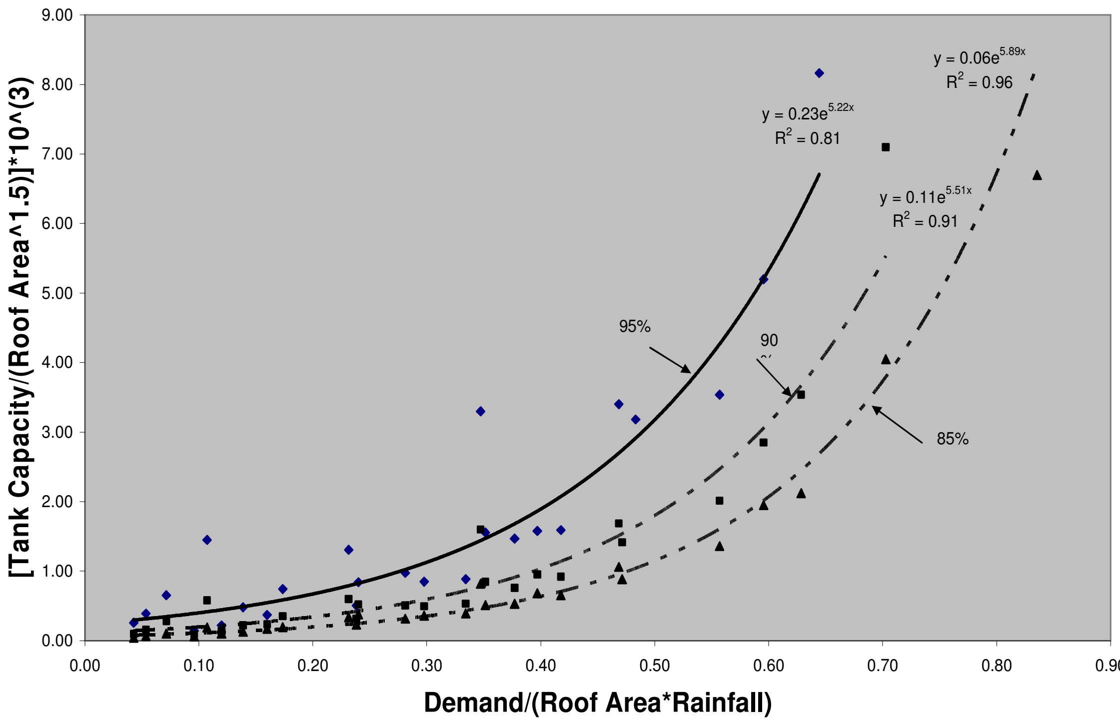

Figure A 4 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Cranbourne)

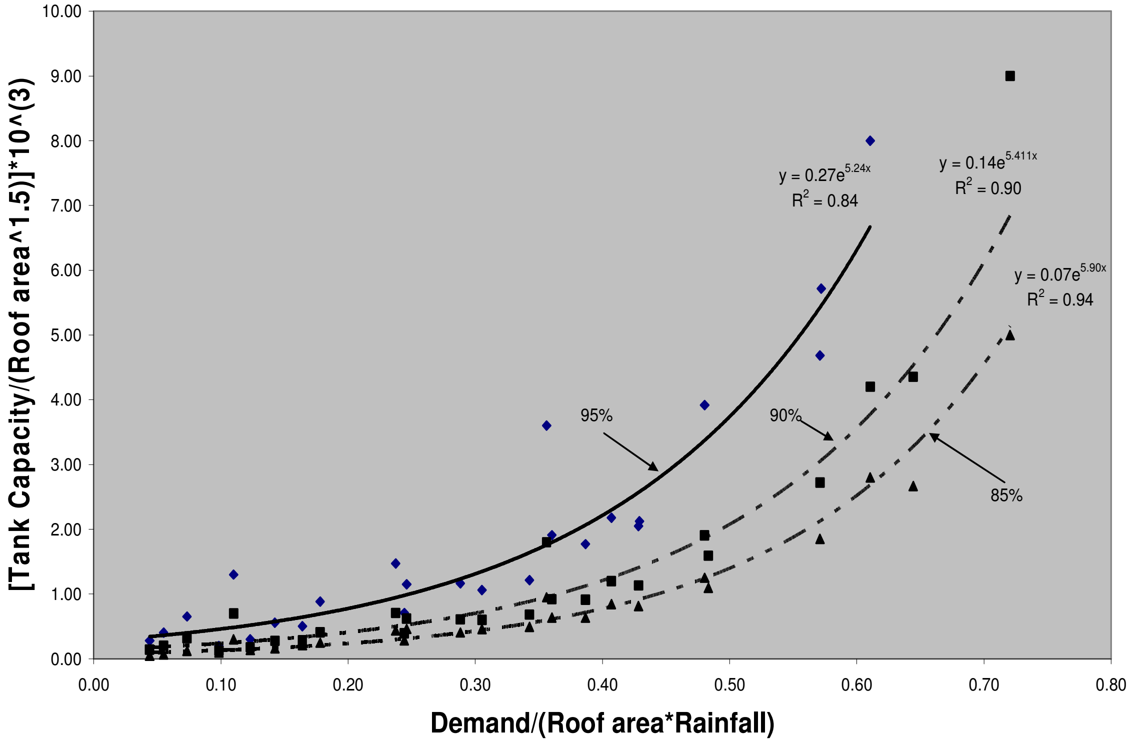

Figure A 5 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Eastern golf club)

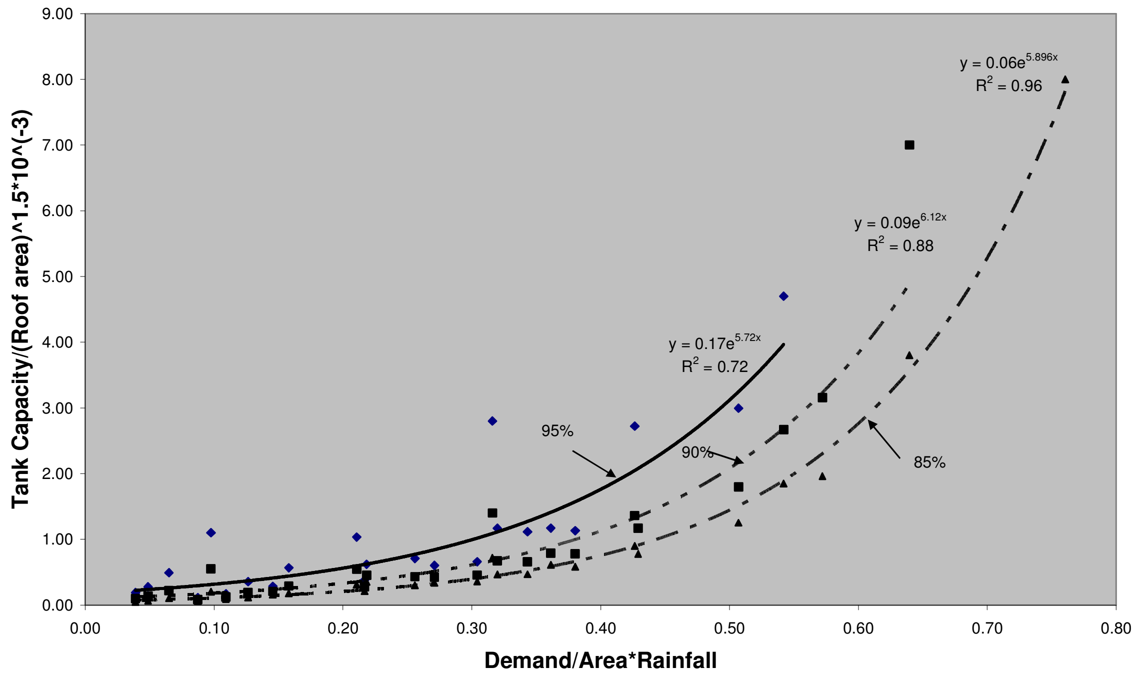

Figure A 6 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (East Doncaster)

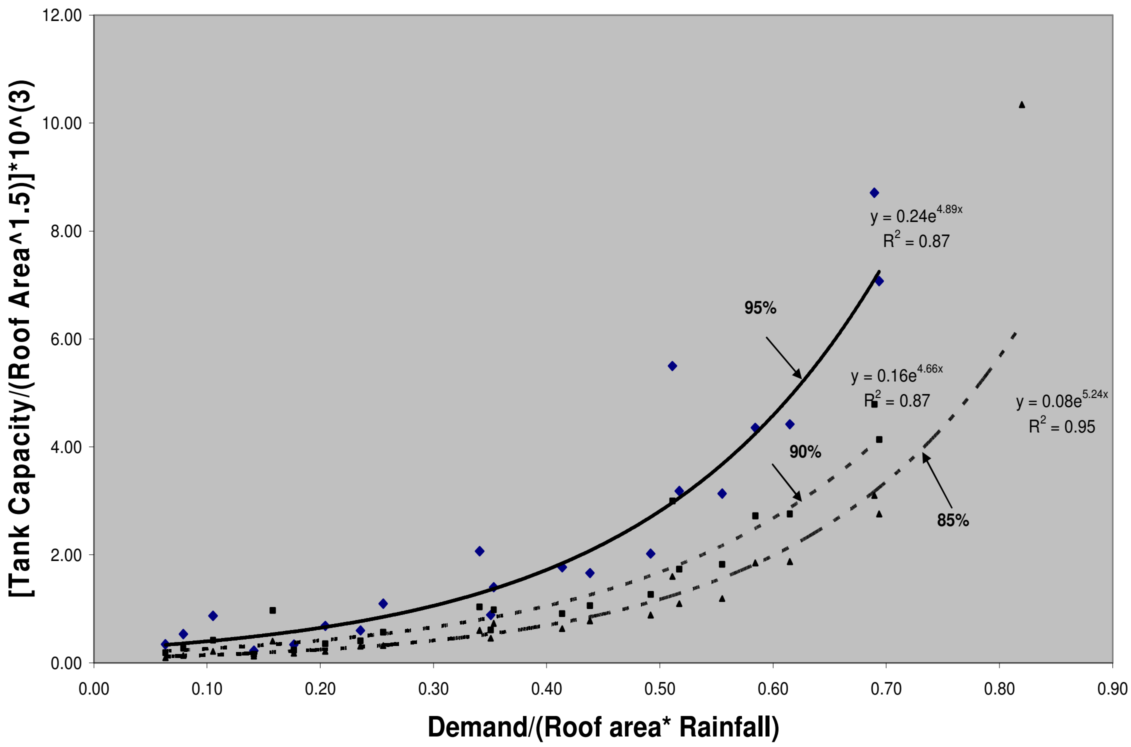

Figure A 7 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Sunshine)

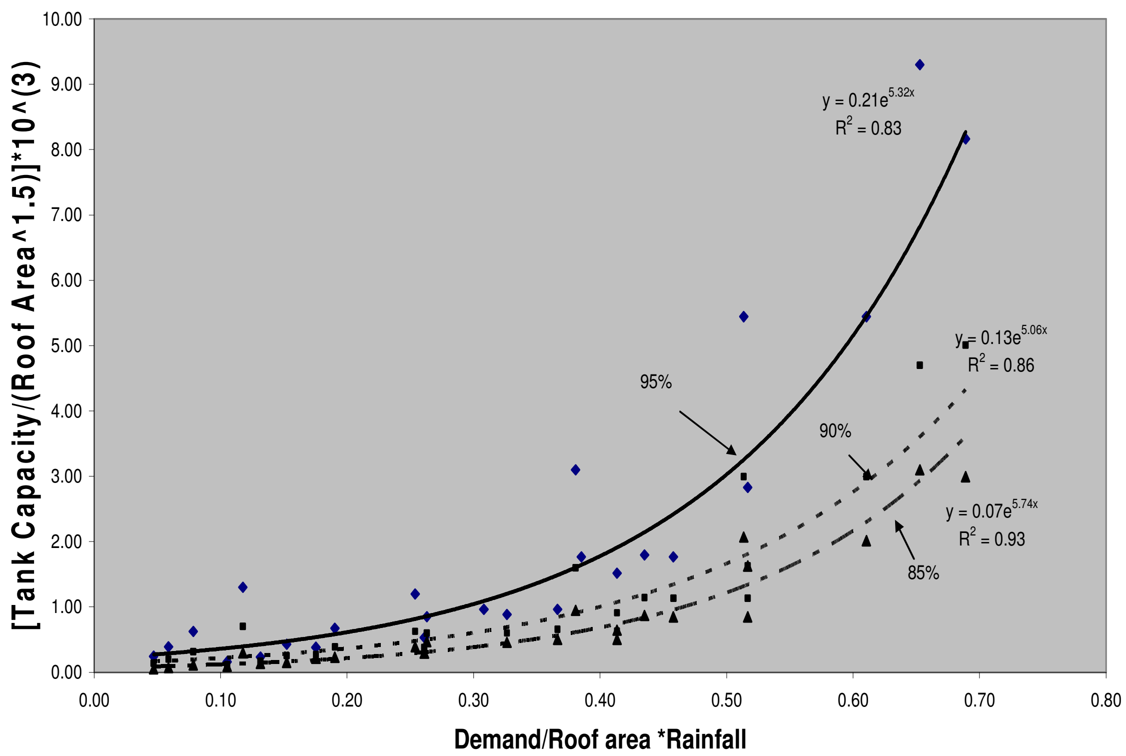

Figure A 8 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Hampton)

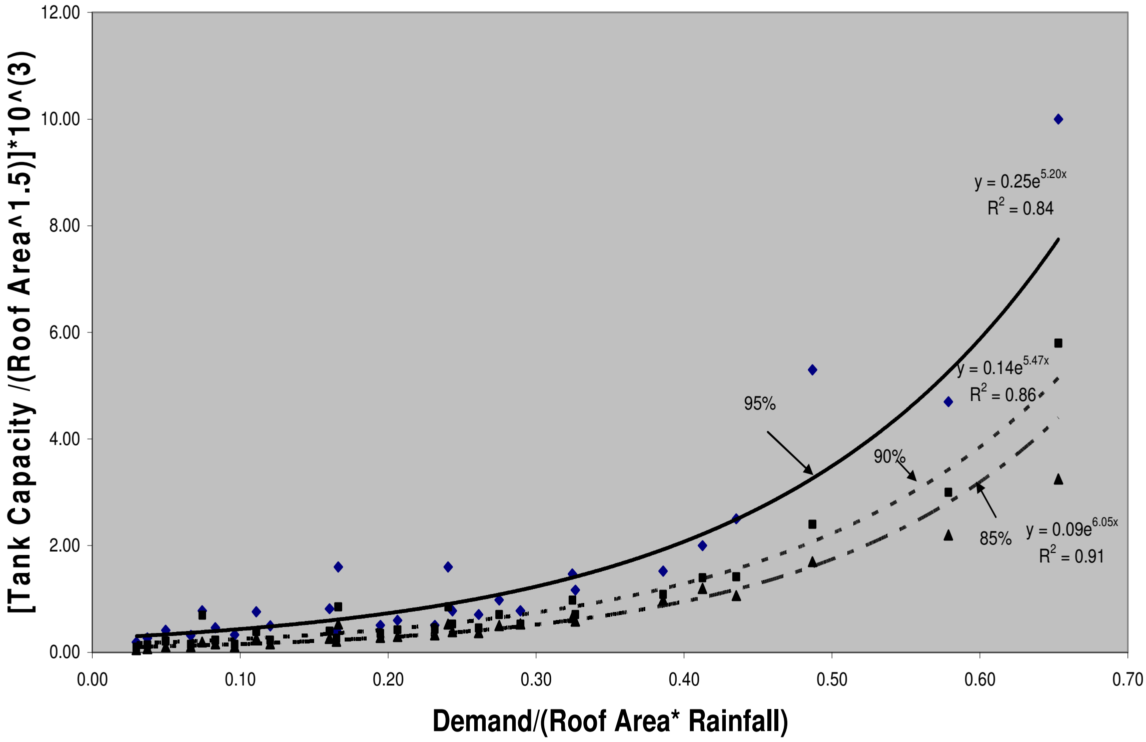

Figure A 9 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Kinglake)

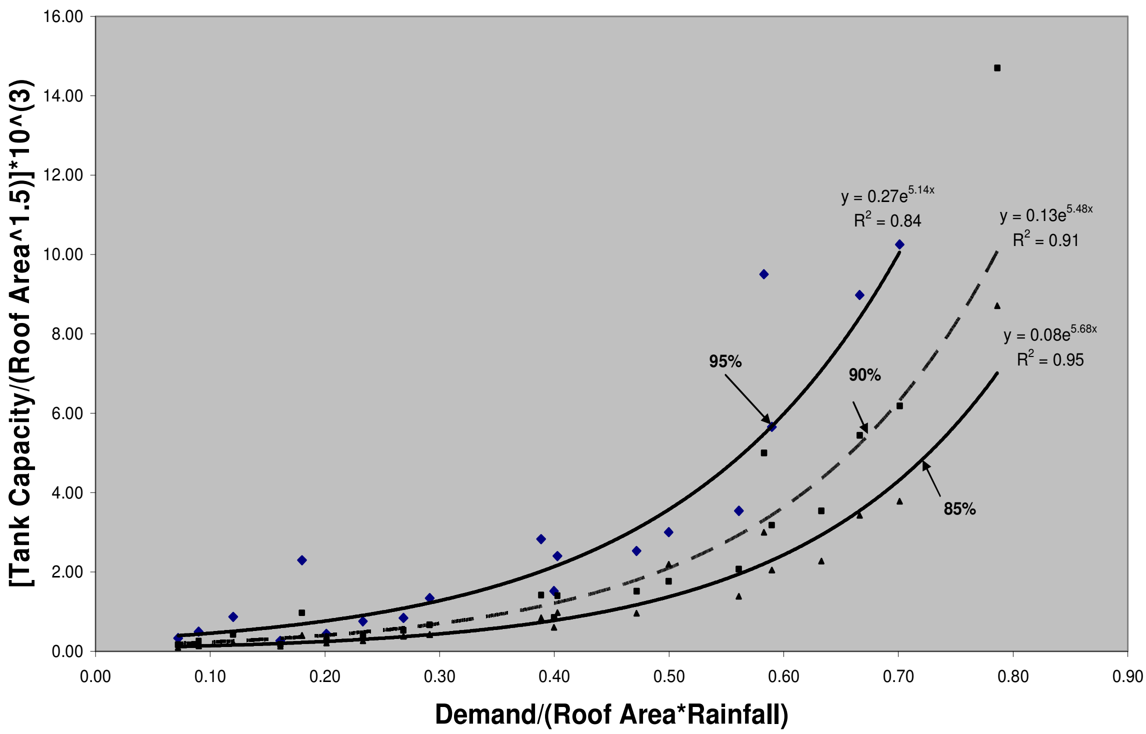

Figure A 10 Relationship between rainwater tank sizes demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Werribee)

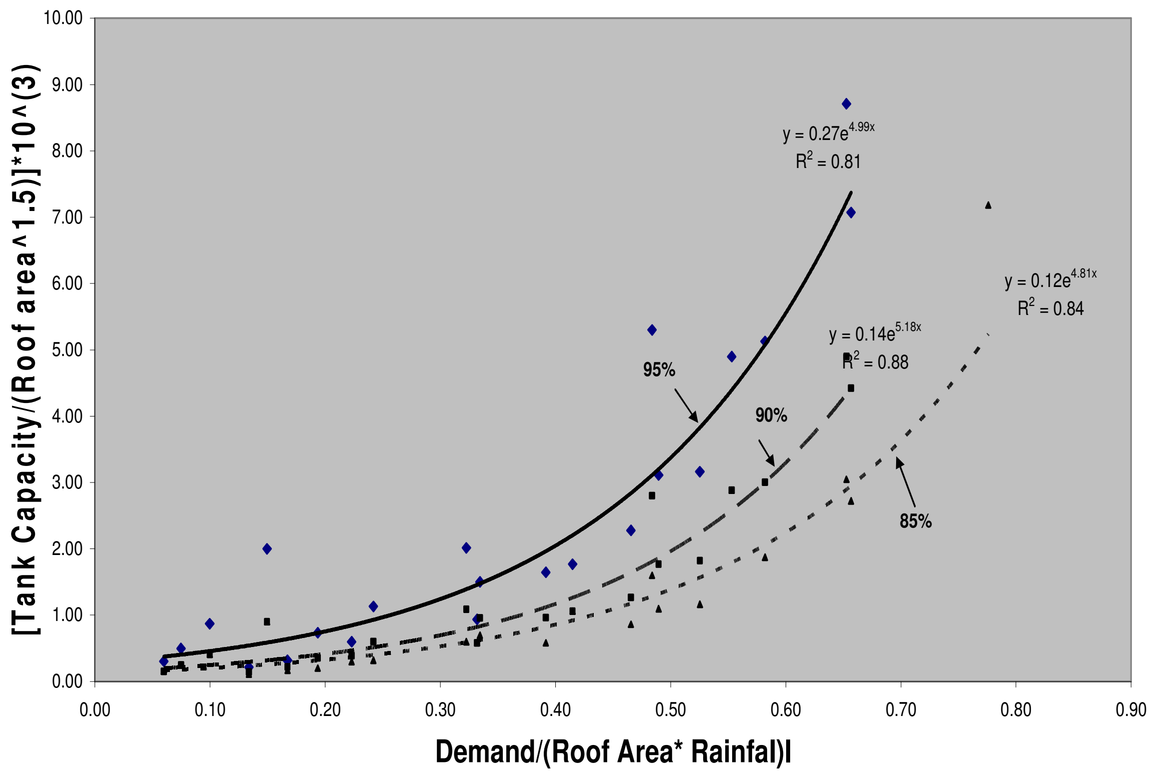

Figure A 11 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (St. Albans)

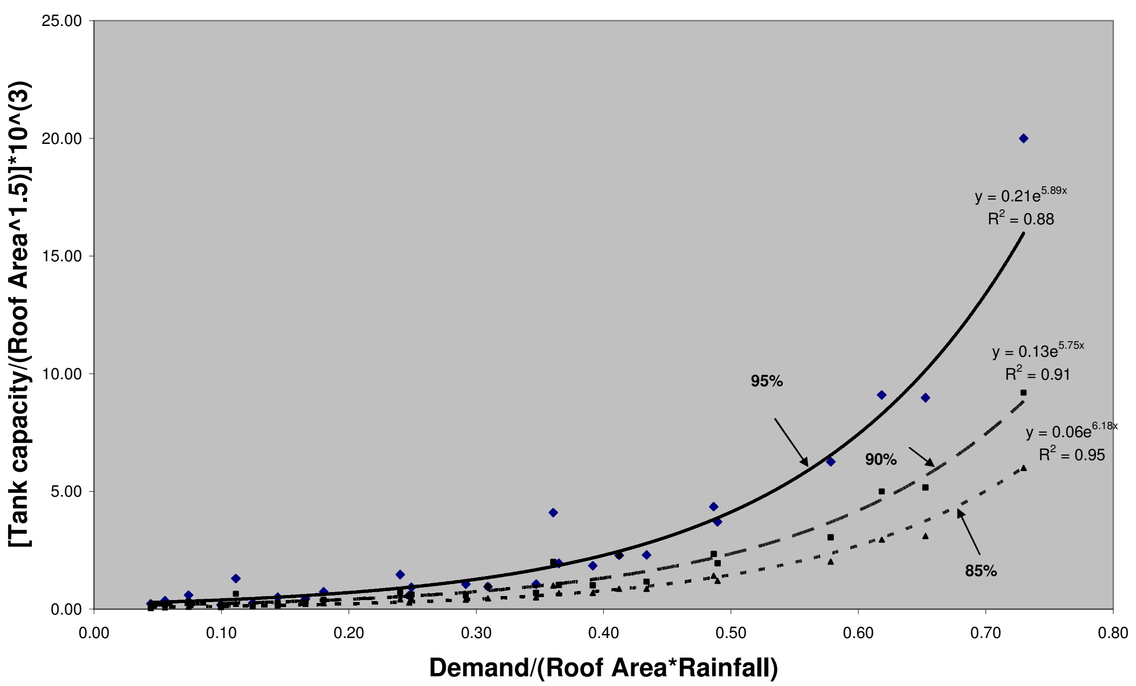

Figure A 12 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Mountview)

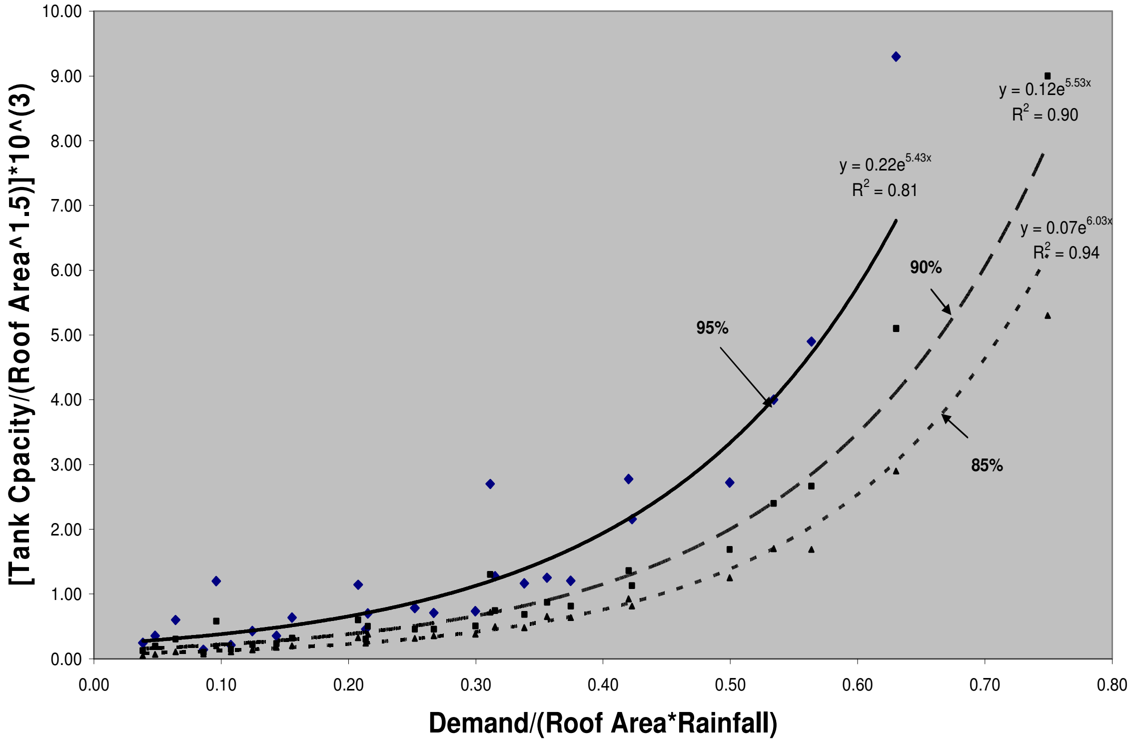

Figure A 13 Relationship between rainwater tank sizes demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Mitcham)

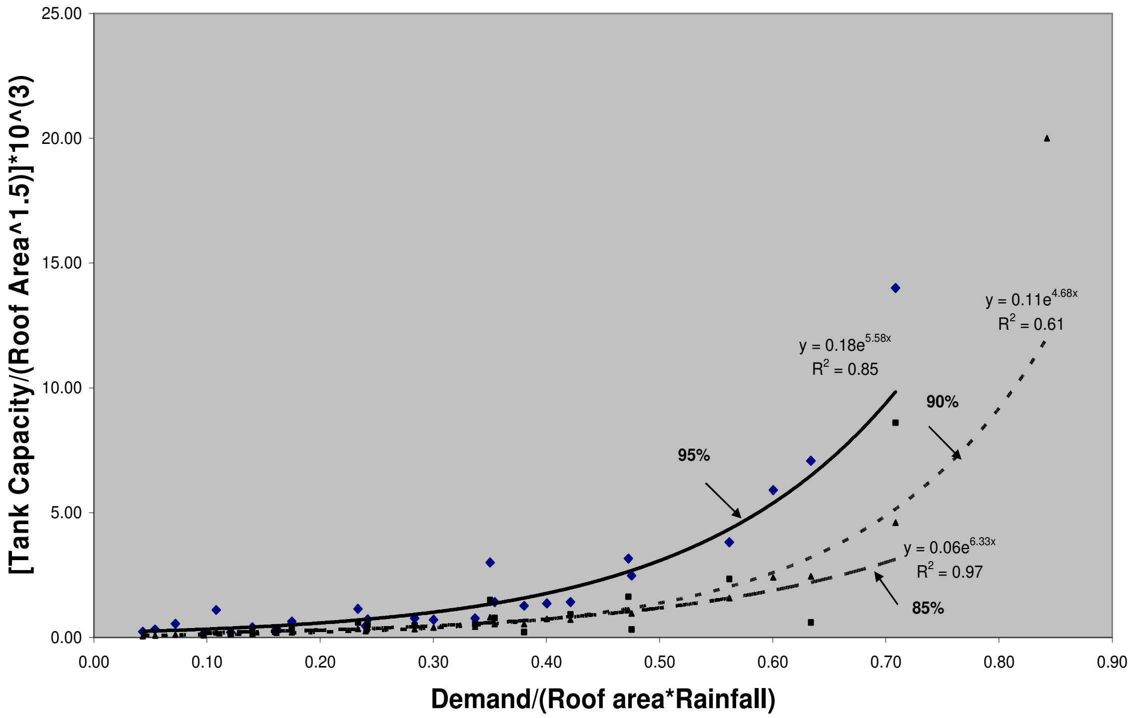

Figure A 14 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Surrey Hills)

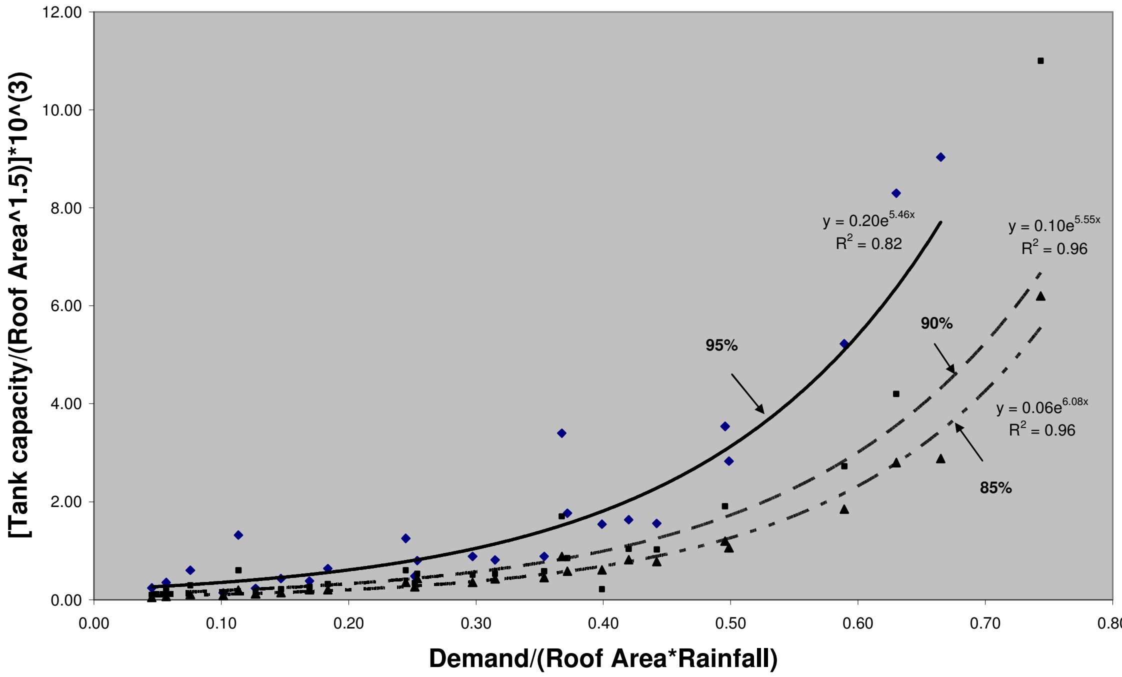

Figure A 15 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Kew)

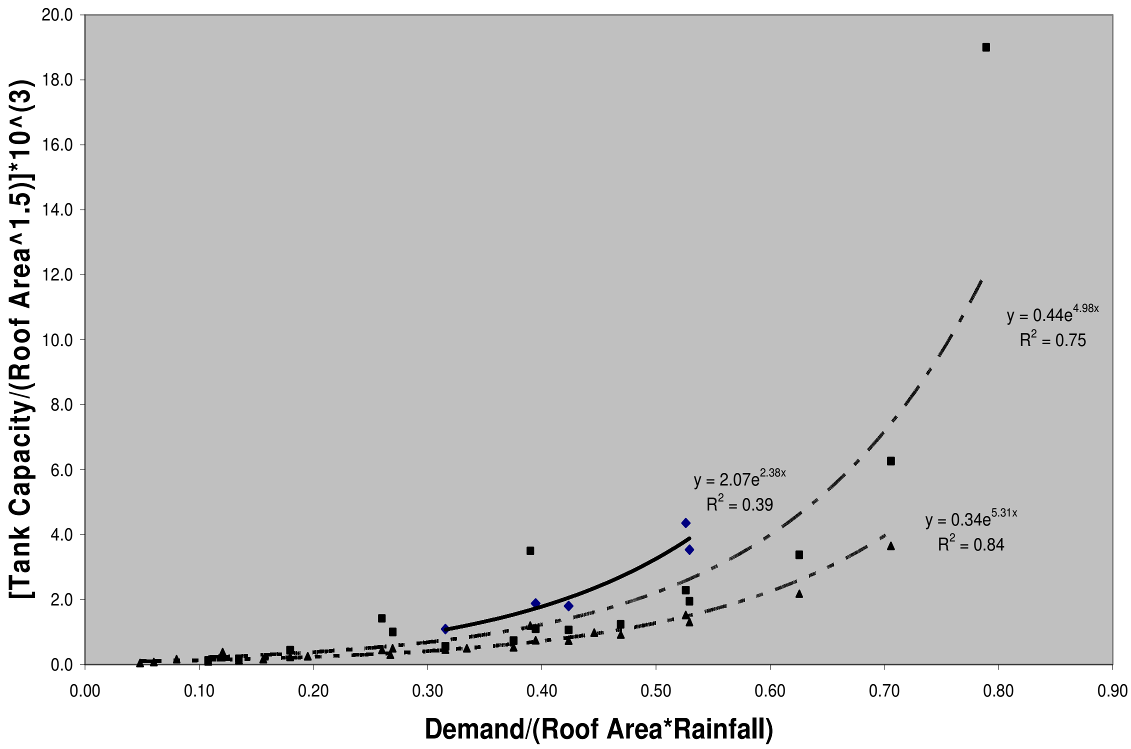

Figure A 16 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Caulfield)

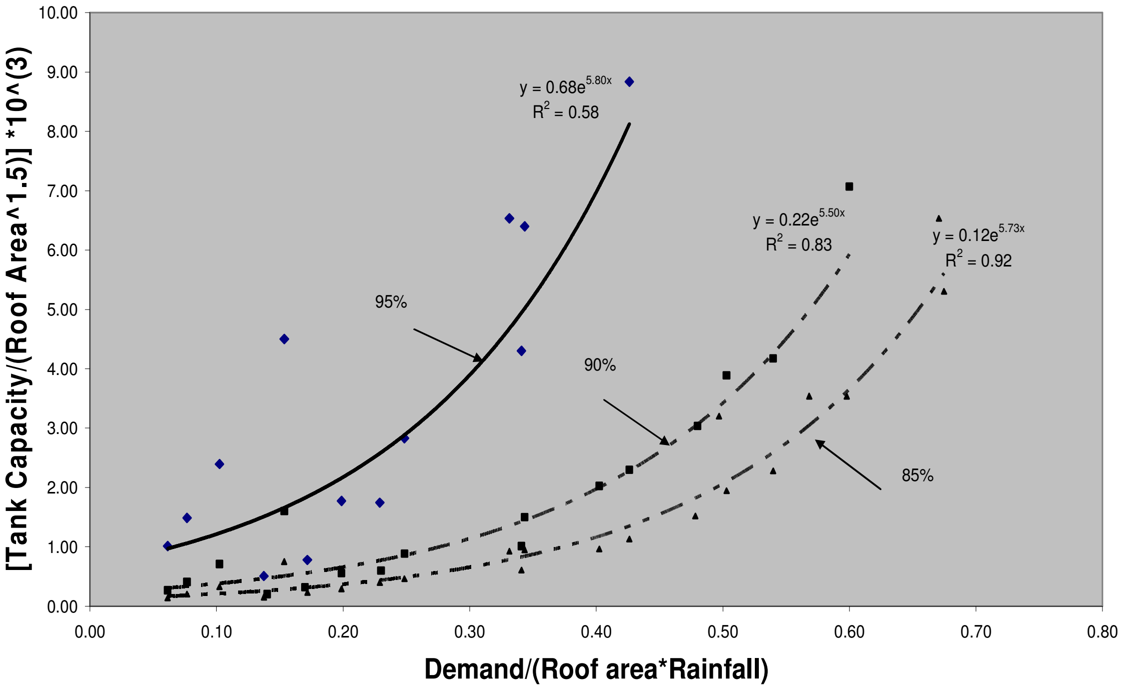

Figure A 17 Relationship between rainwater tank sizes with demand (D), roof area (A) and mean annual rainfall (MAR) for different water supply reliability (Altona)

Appendix B

***Regression Analysis** (Between The Tank Sizes Calculated From The Regression Equation (Generalized Curve) And The Water Balance Model)*

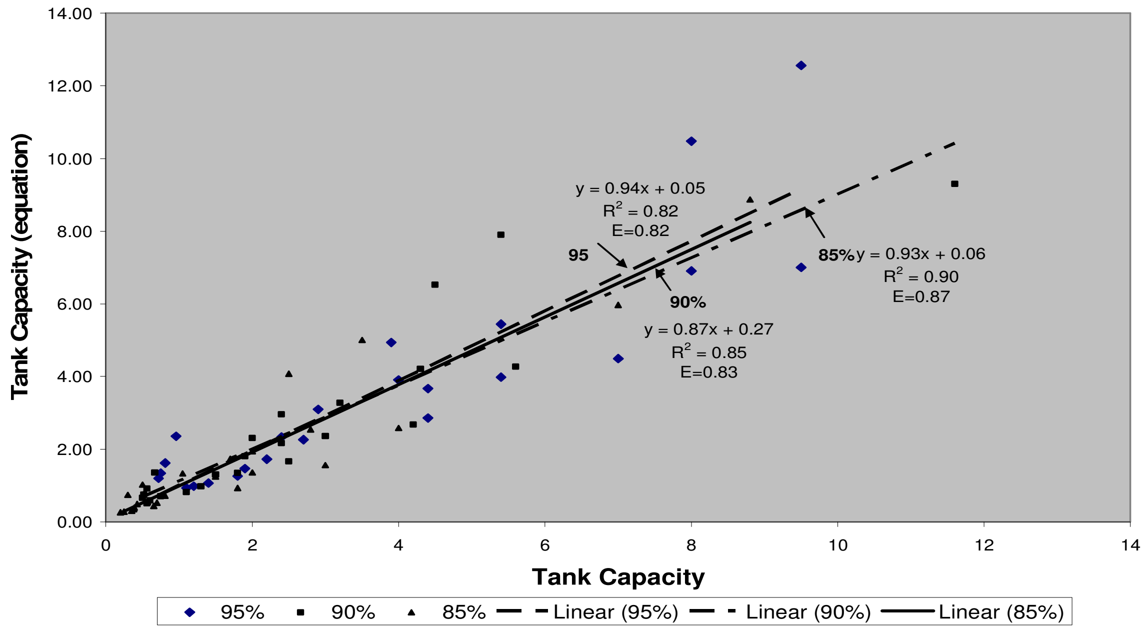

Figure B1 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Arthur Creek)

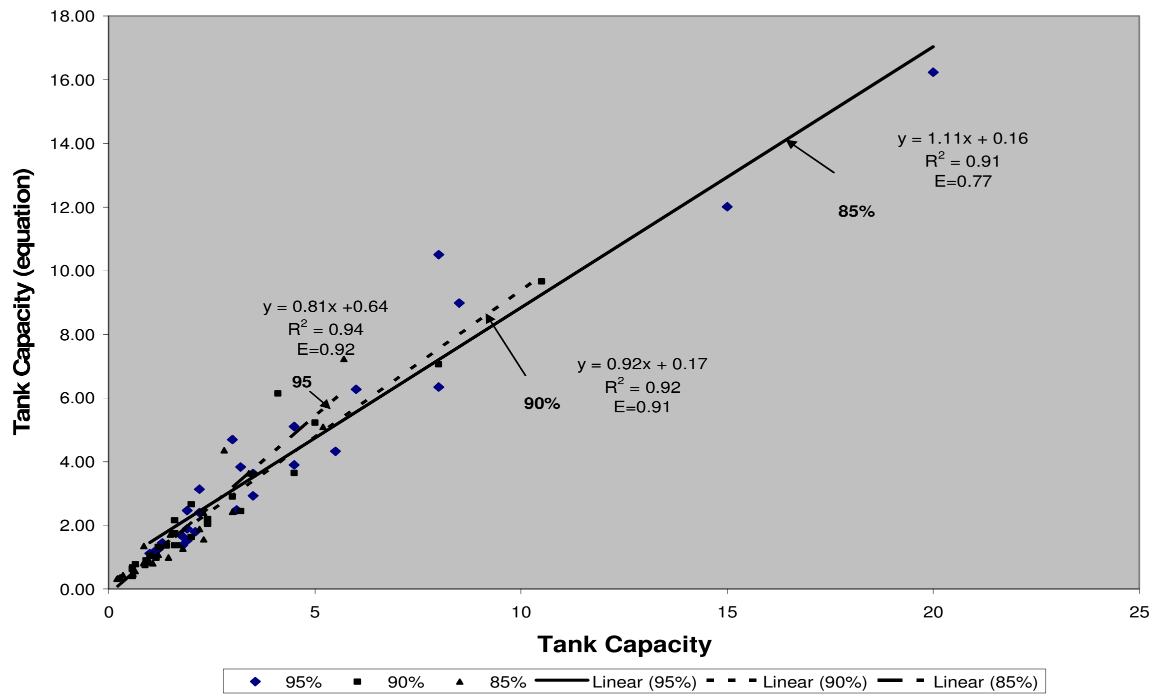

Figure B2 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Sandringham)

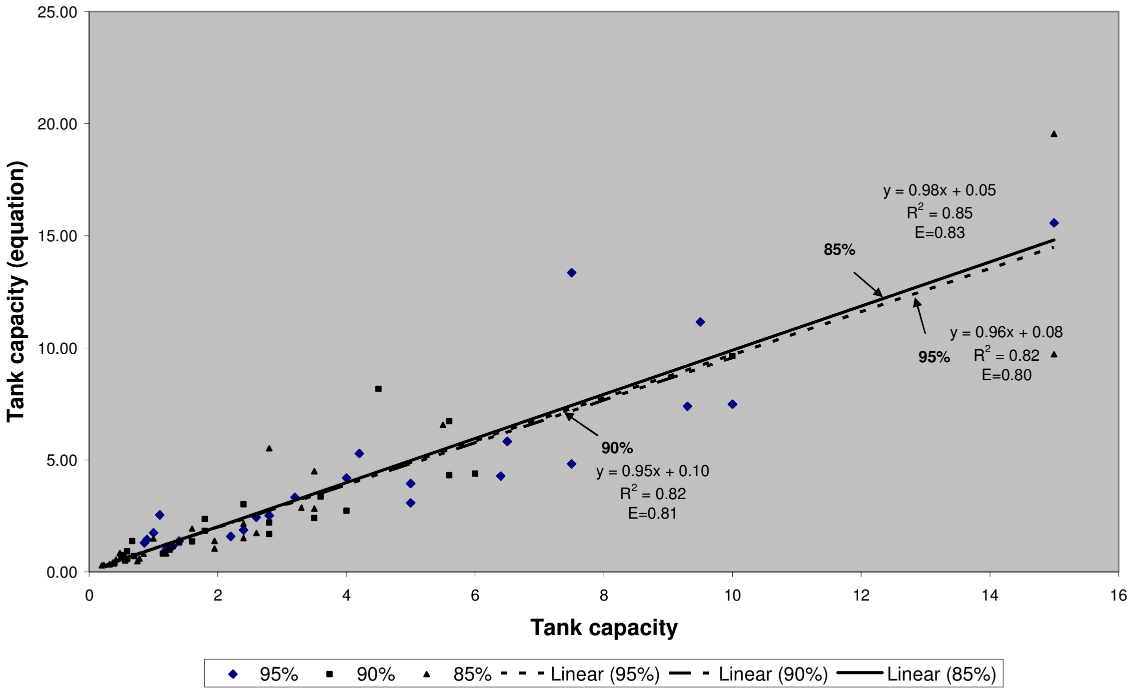

Figure B3 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Notting Hill)

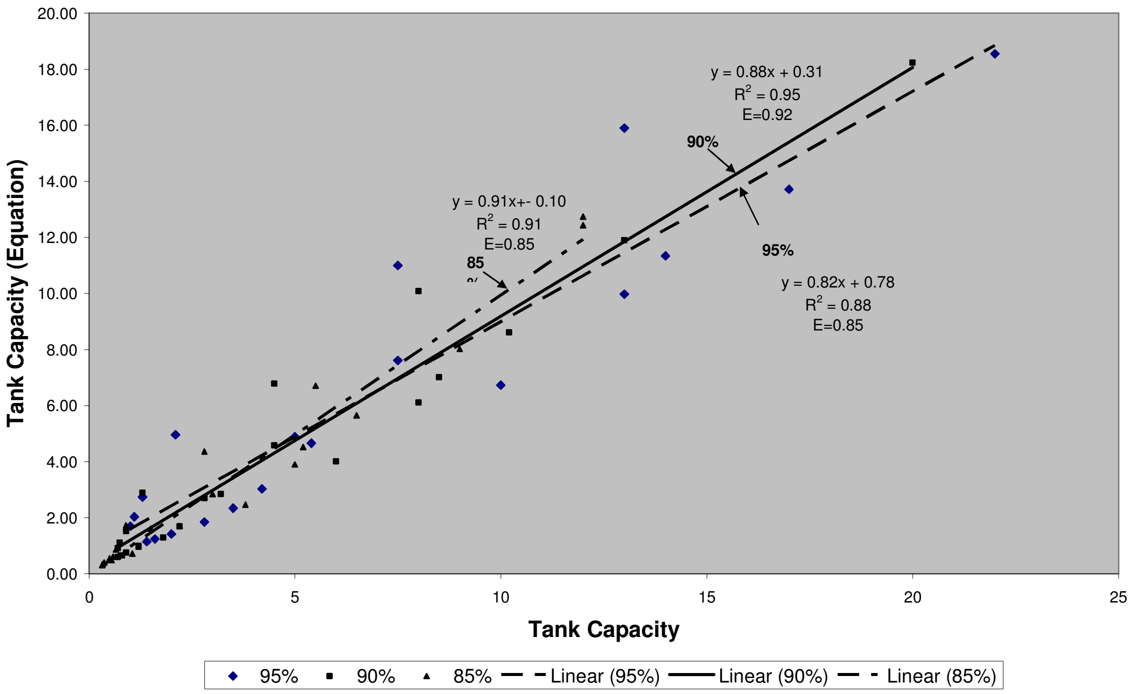

Figure B4 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Rockbank)

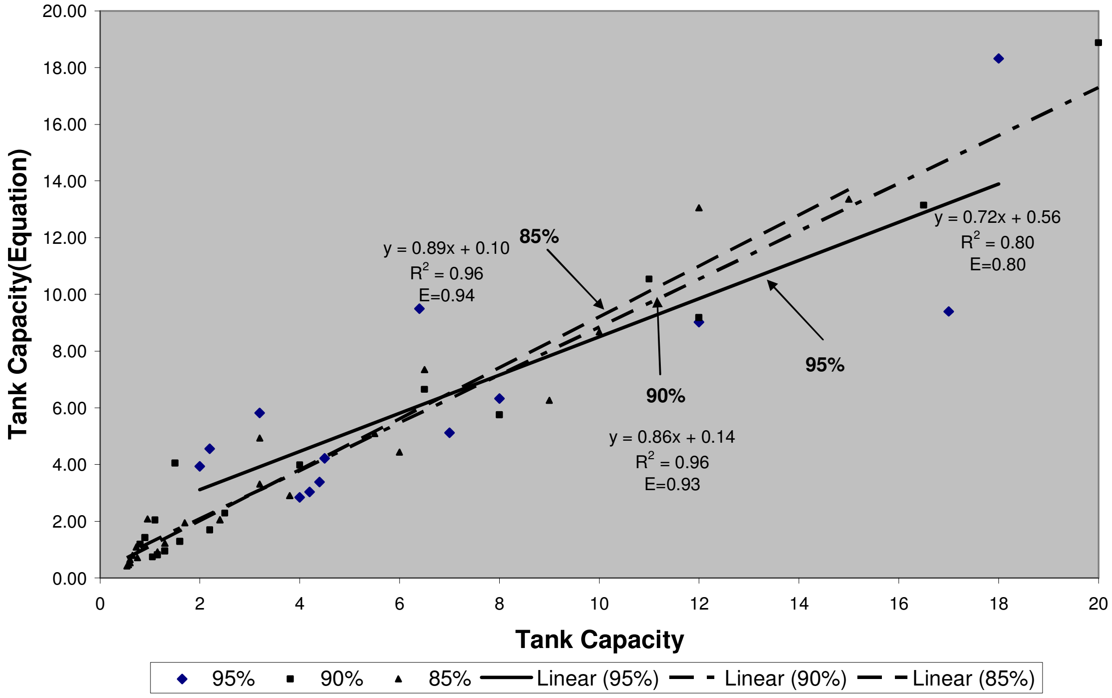

Figure B5 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Altona)

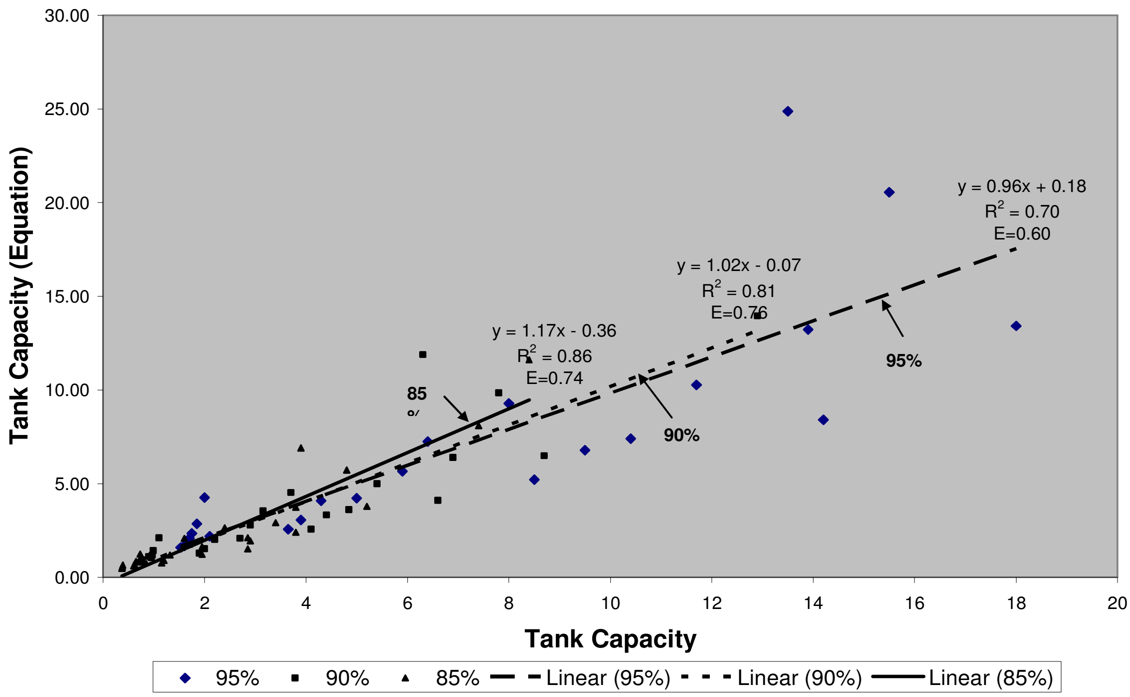

Figure B6 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Berwick)

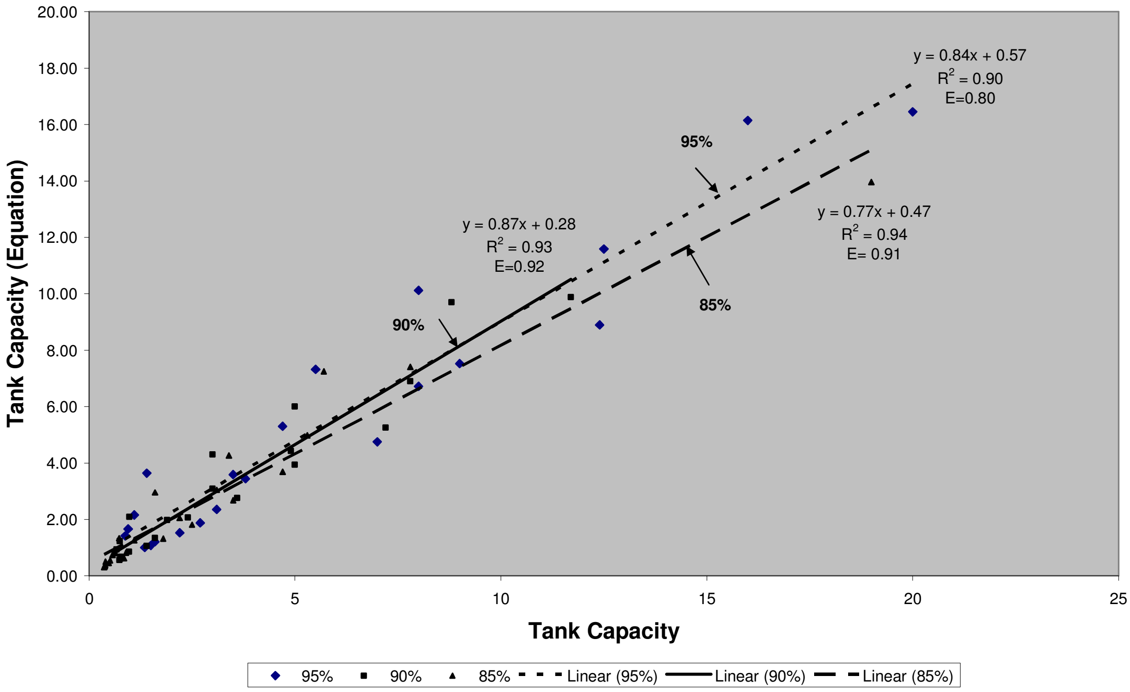

Figure B7 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Sunshine)

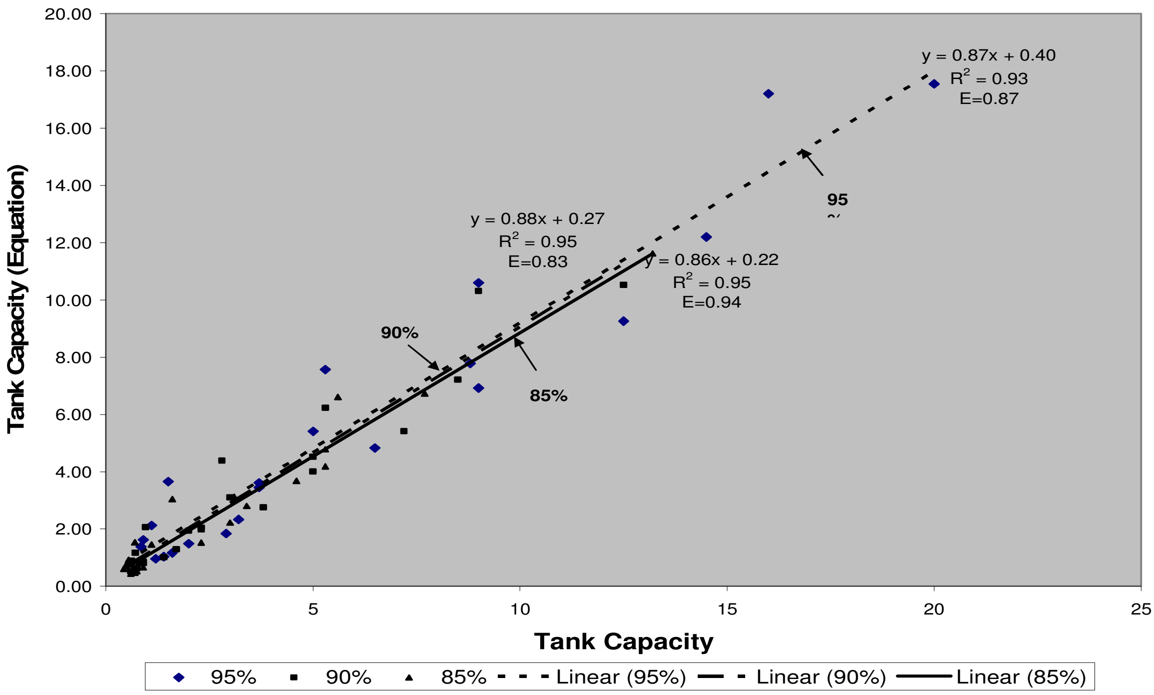

Figure B8 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (St. Albans)

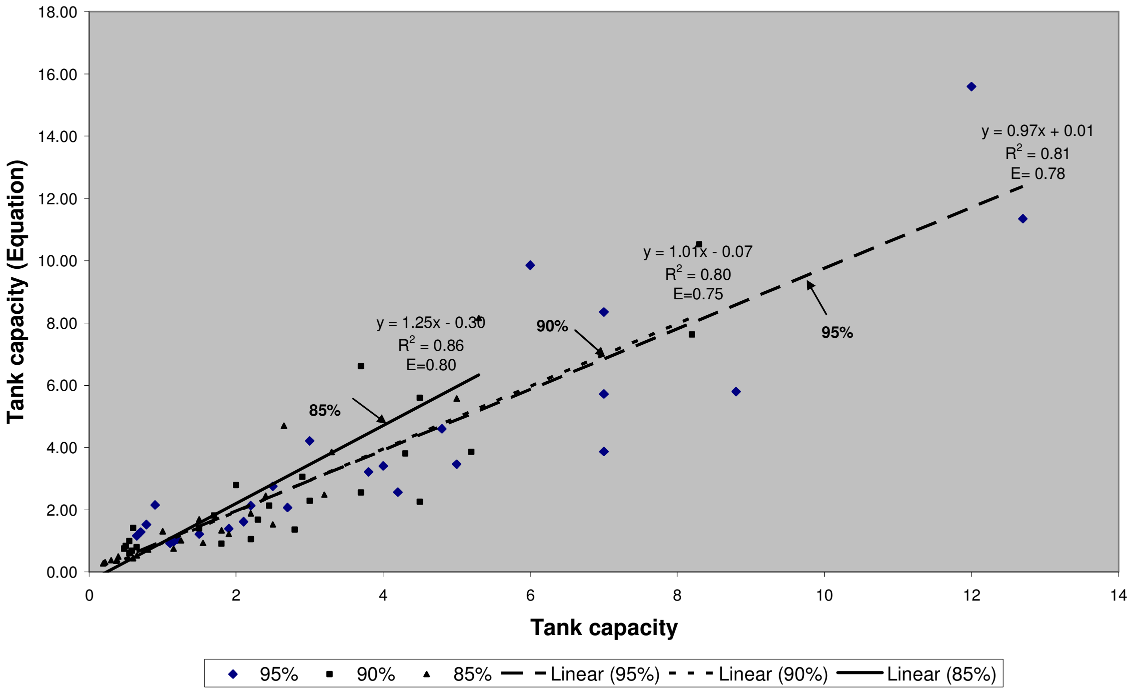

Figure B9 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Caulfield North)

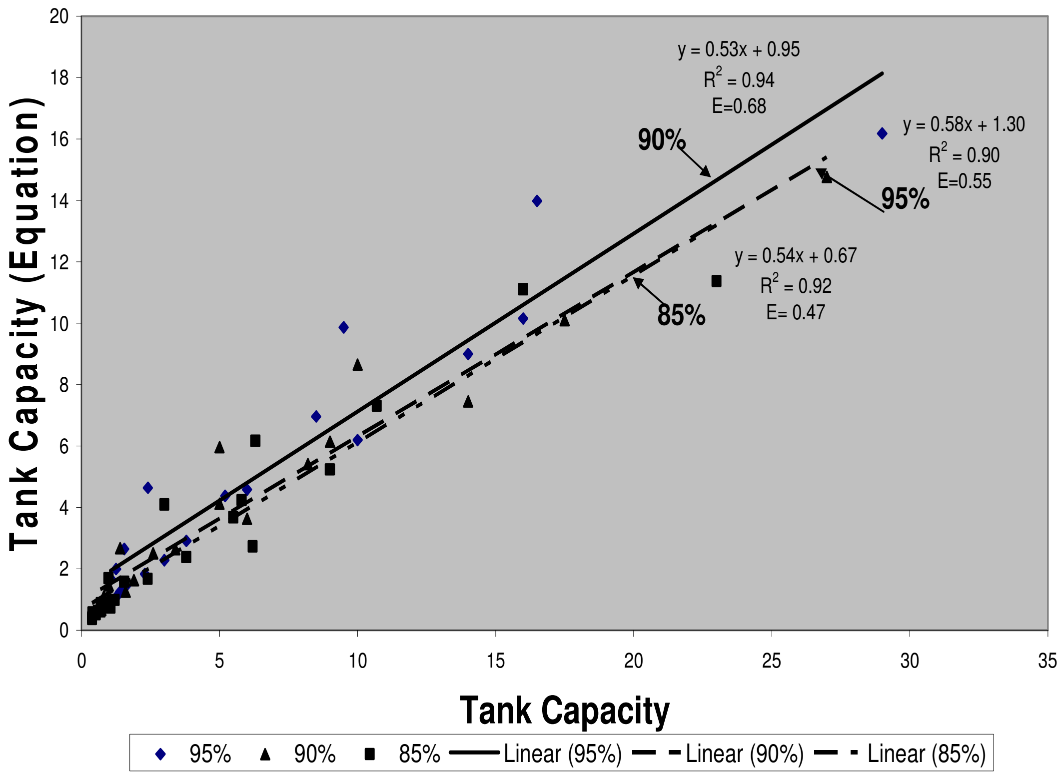

Figure B10 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Werribee)

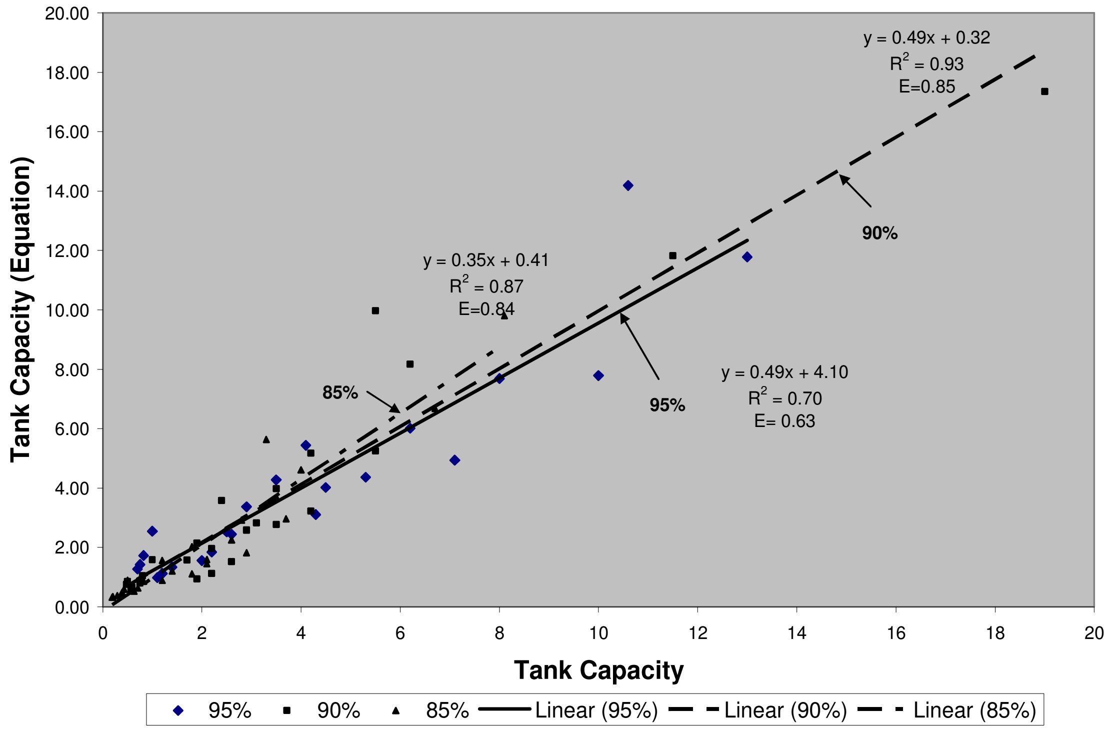

Figure B11 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Caulfield)

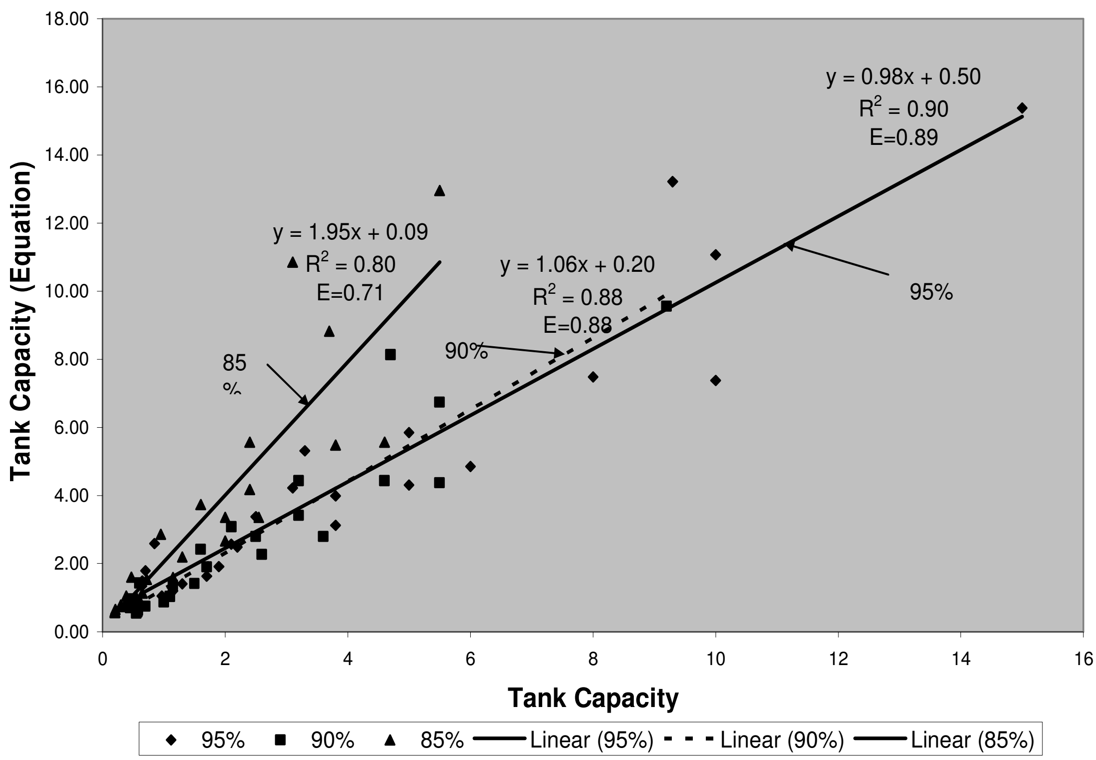

Figure B12 Comparison between the tank sizes calculated from the regression equation (Generalized curve) and the water balance model (Hampton)

Relationship Between Demand (D), Roof Area (A), Rainfall (R), Tank Capacity (C) And Reliability For Greater Melbourne For Different Roof Areas

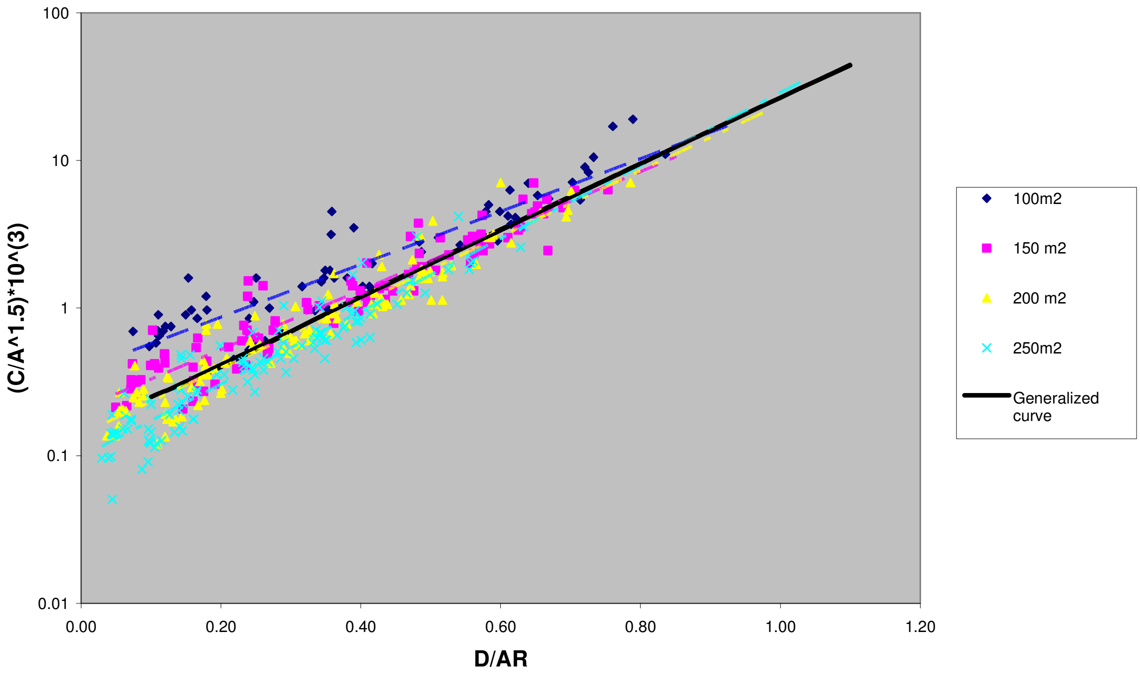

Figure B13 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different roof areas (90% reliability)

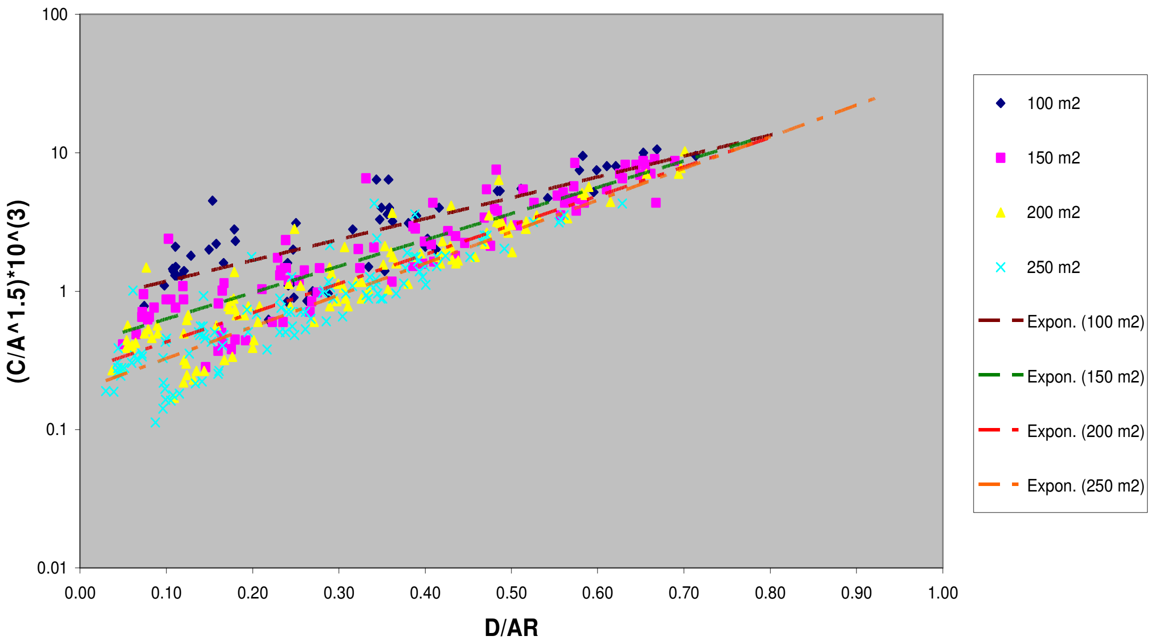

Figure B14 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different roof areas (95% reliability)

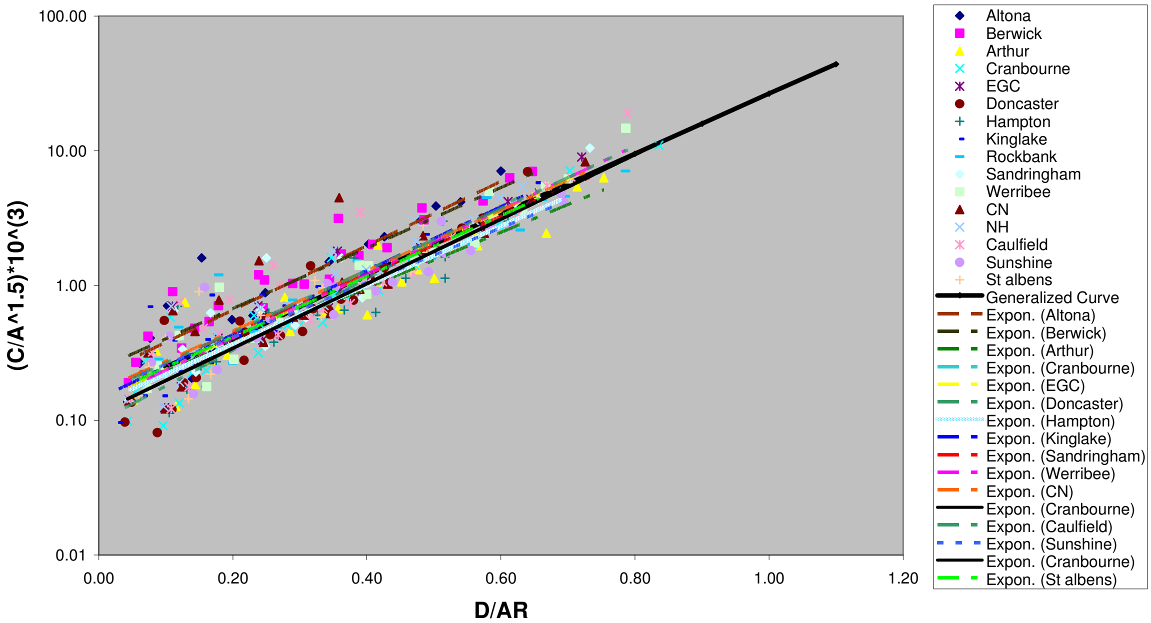

Figure B15 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different rainfall (90% reliability)

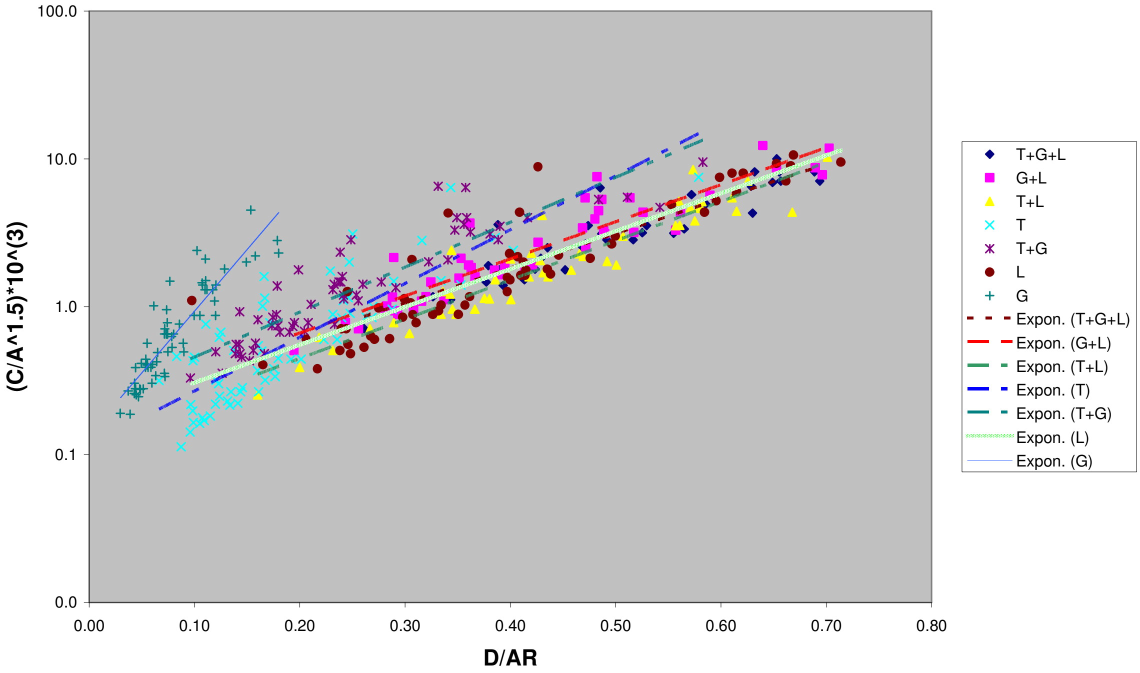

Figure B16 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different rainfall (95% reliability)

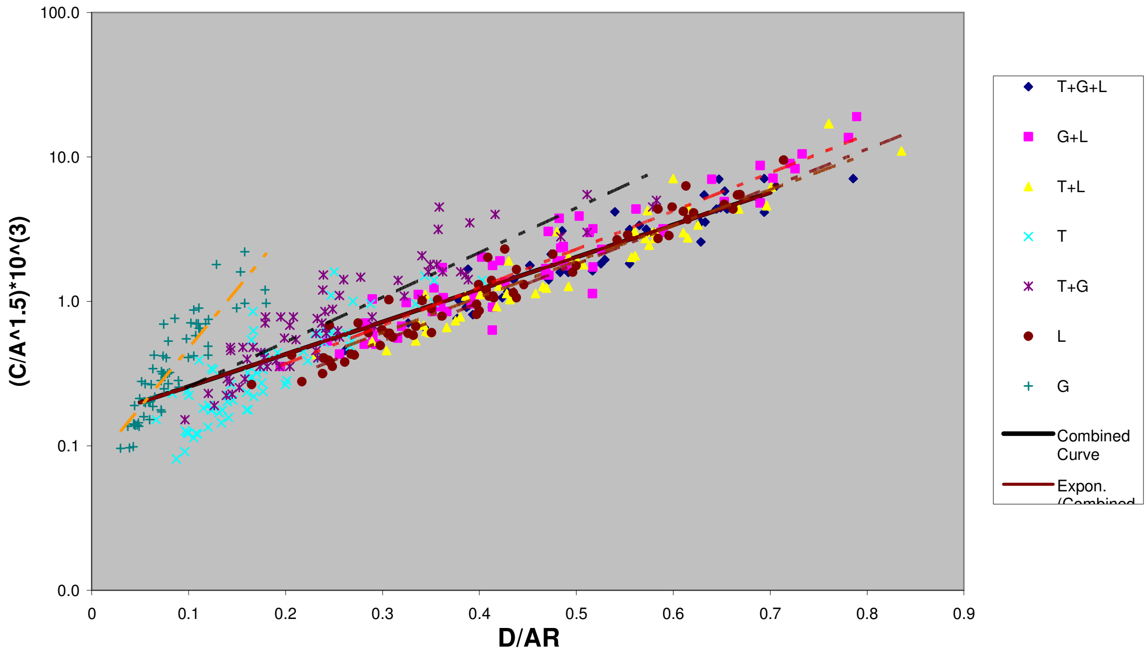

Figure B17 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different demand (90% reliability)

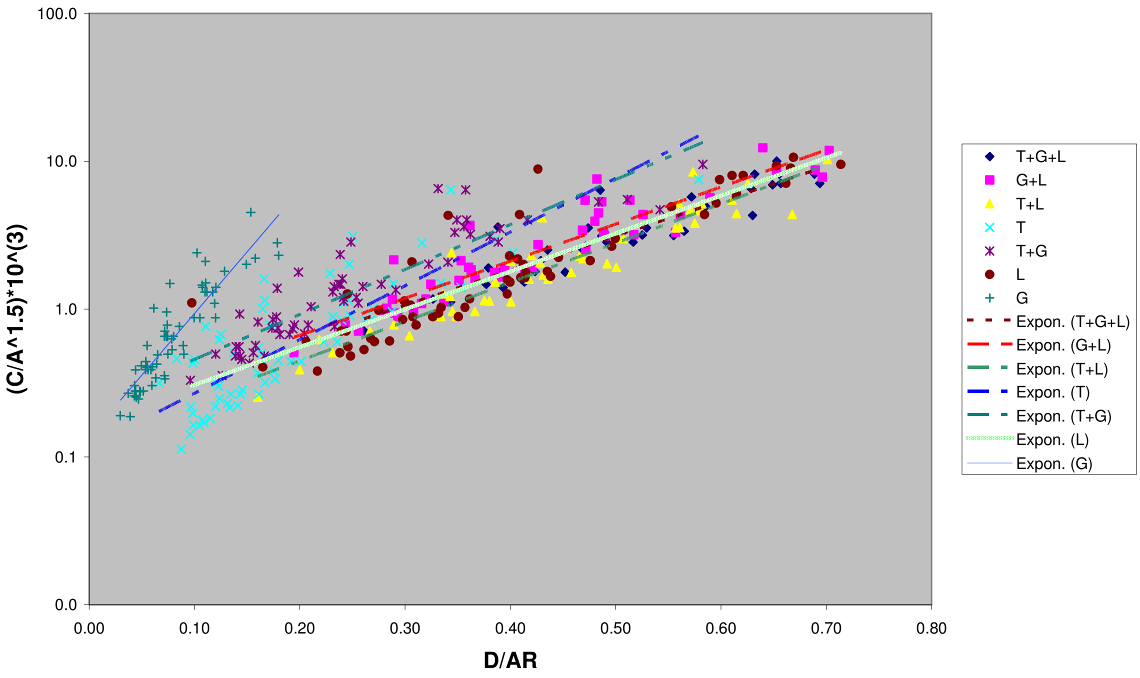

Figure B18 Relationship between demand, roof area, rainfall, tank capacity and reliability for Greater Melbourne for different demand (95% reliability)

Appendix C

The Relationship between Tank Sizes and Reliabilities

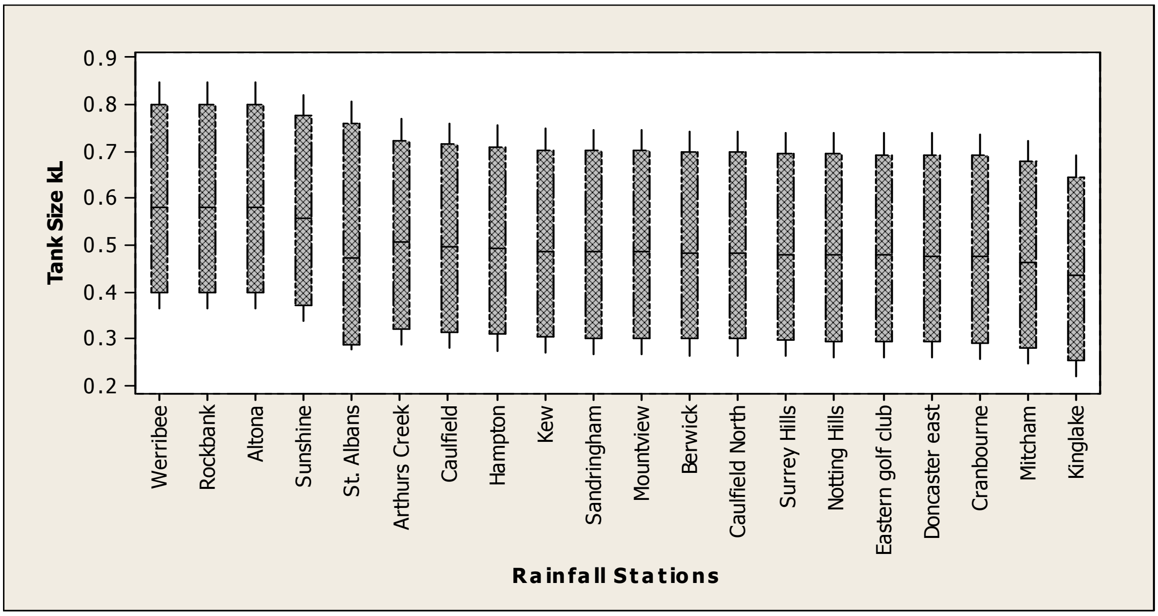

Figure C1 Variation in tank sizes from roof areas at different locations across Melbourne for 90% reliability and garden use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

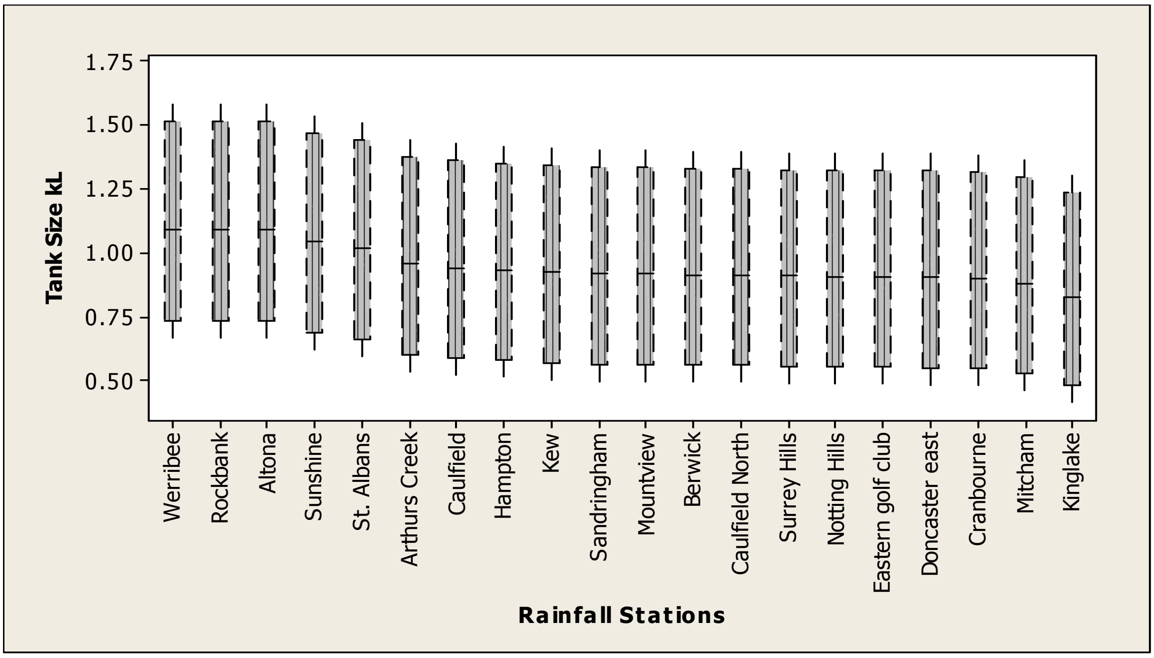

Figure C2 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and garden use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

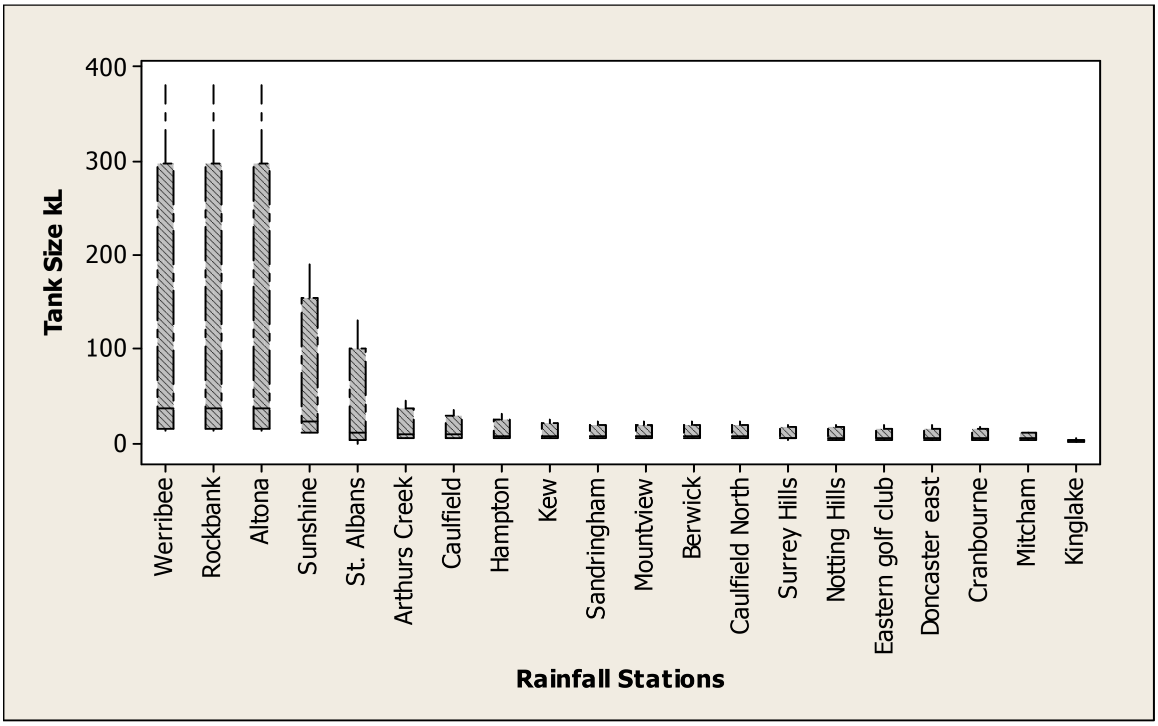

Figure C3 Variation in tank sizes from roof areas at different locations across Melbourne for 90% reliability and toilet, garden and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

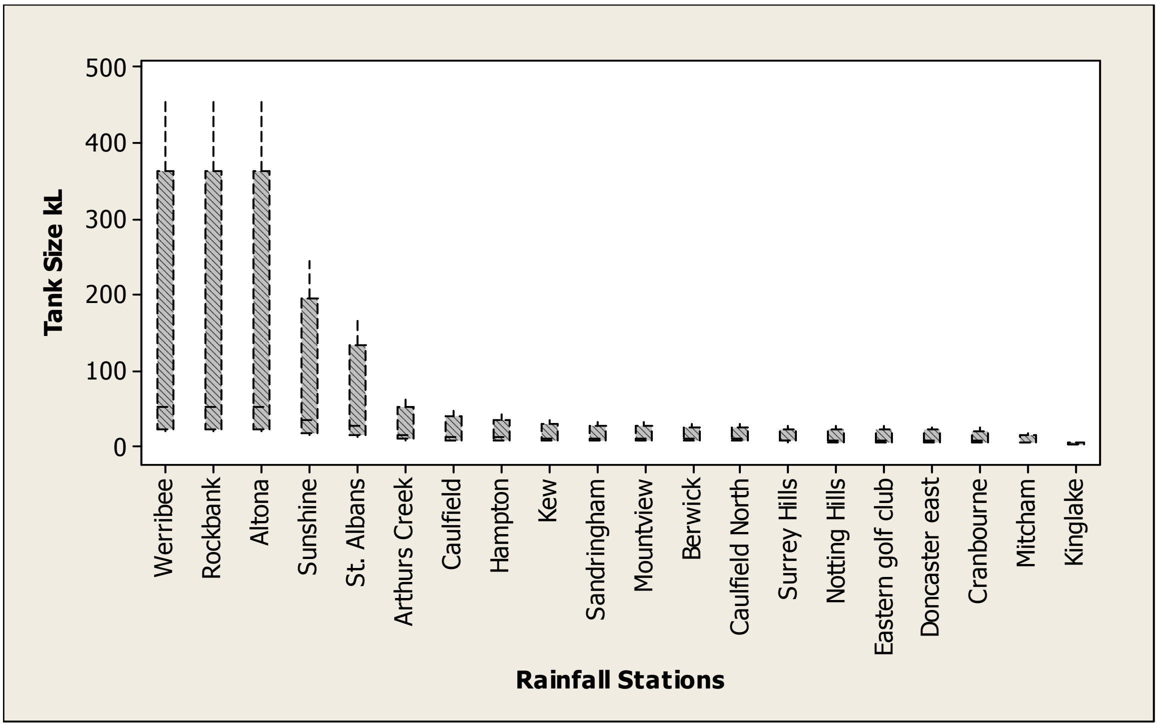

Figure C4 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and toilet, garden and laundry use(lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

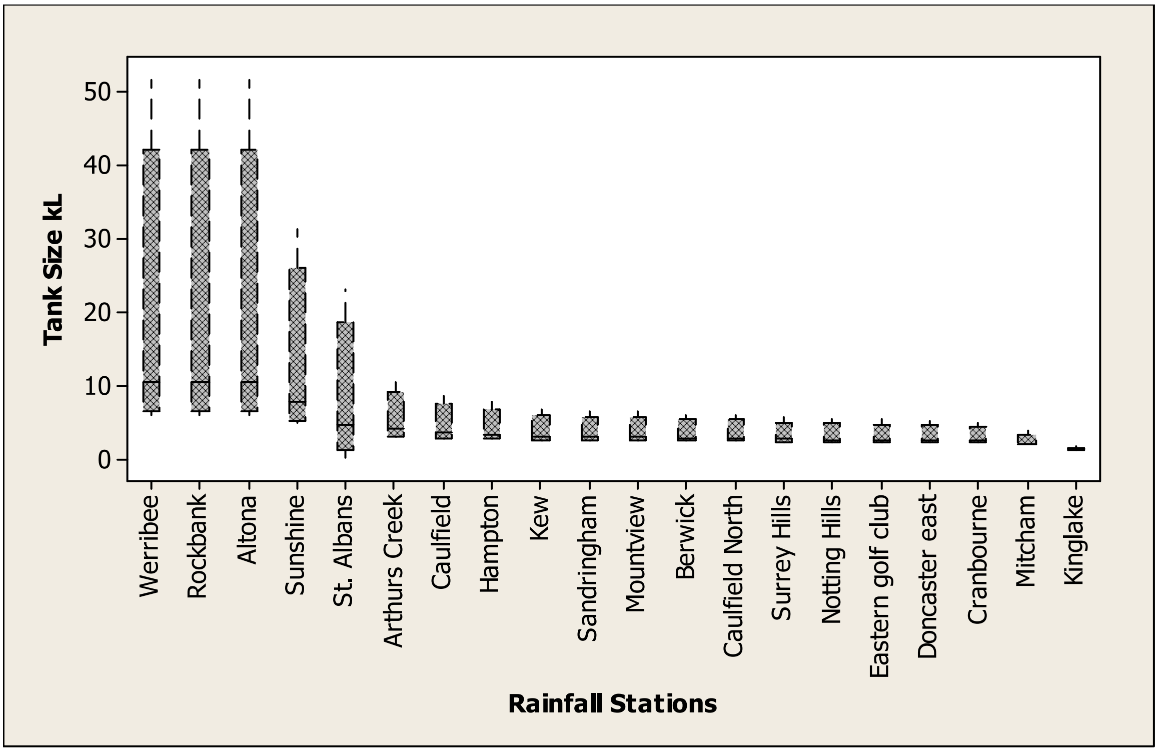

Figure C5 Variation in tank sizes from roof areas at different locations across Melbourne for 90% reliability and garden and laundry use (lower limit is when A = 250 m^2 and upper limit is when A = 100 m^2)

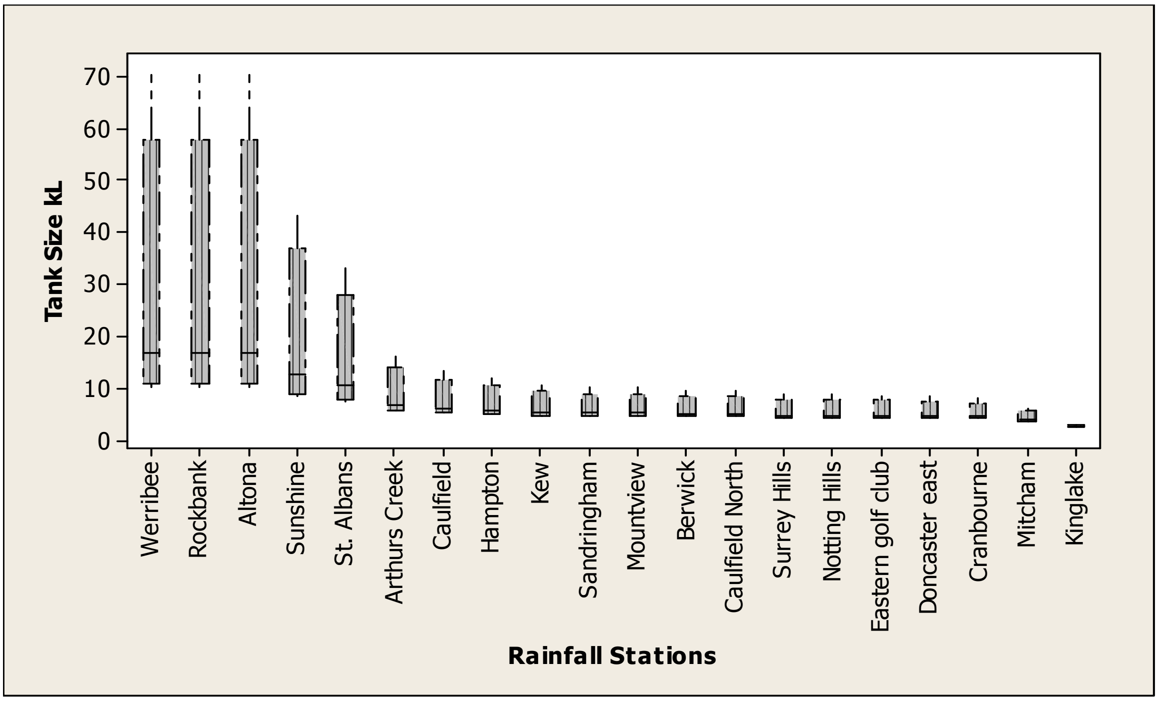

Figure C6 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and toilet, garden and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

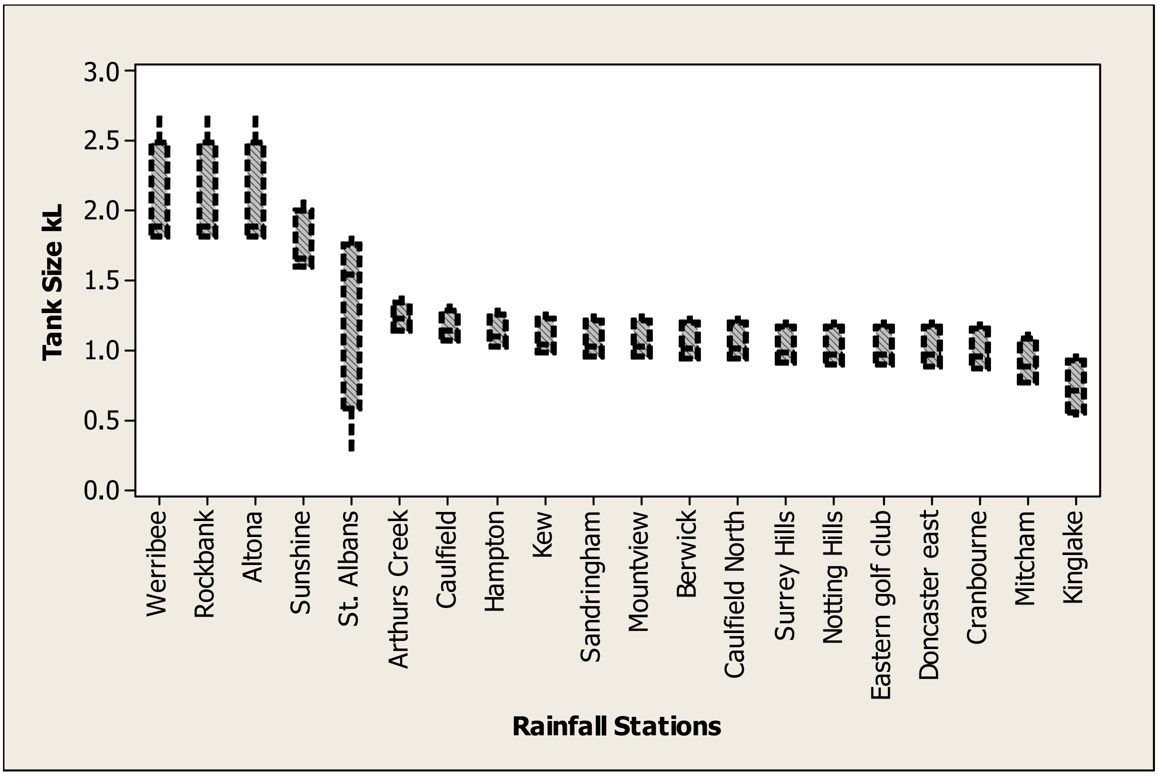

Figure C7 Variation in tank sizes from roof areas at different locations across Melbourne for 90% reliability and toilet and garden use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

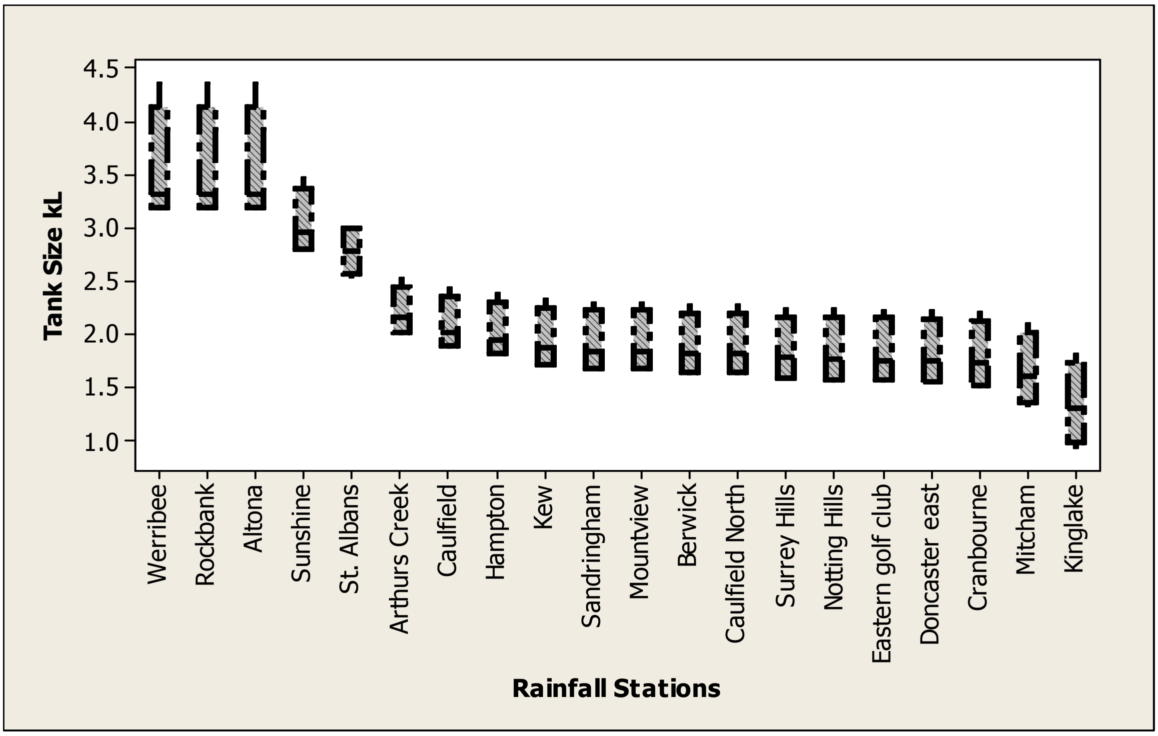

Figure C8 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and toilet, garden and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

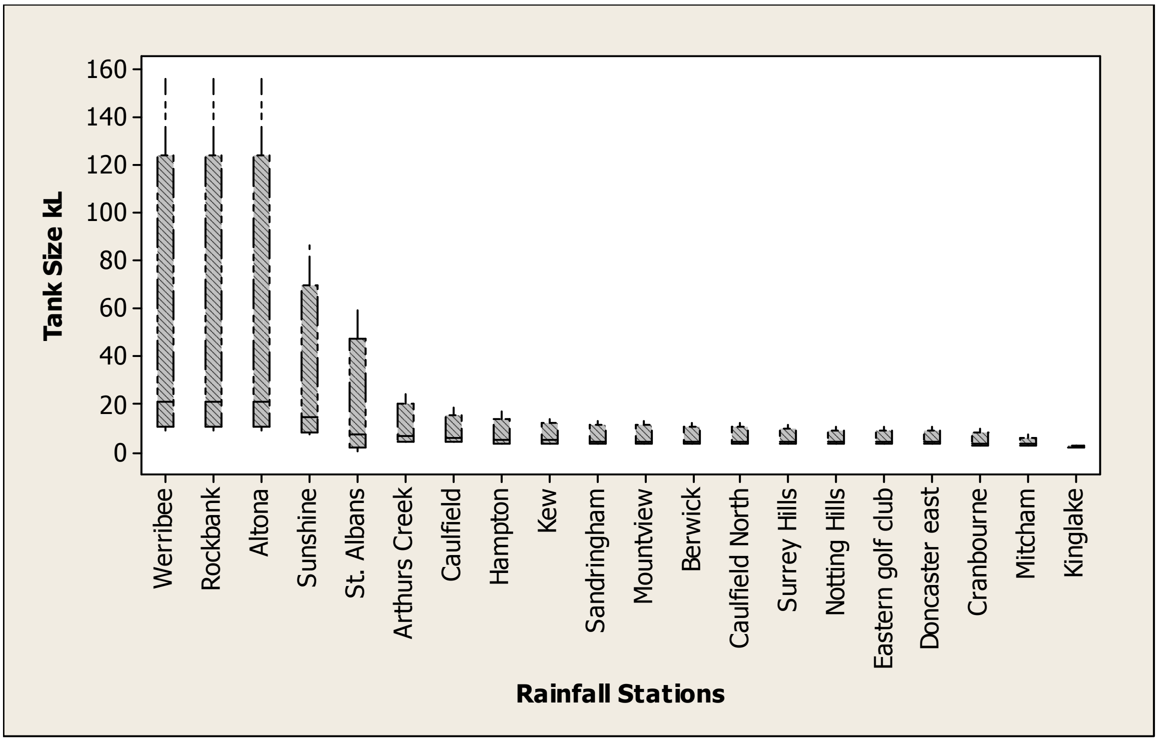

Figure C9 Variation in tank sizes from roof areas at different Locations across Melbourne for 90% reliability and toilet and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100 m^2)

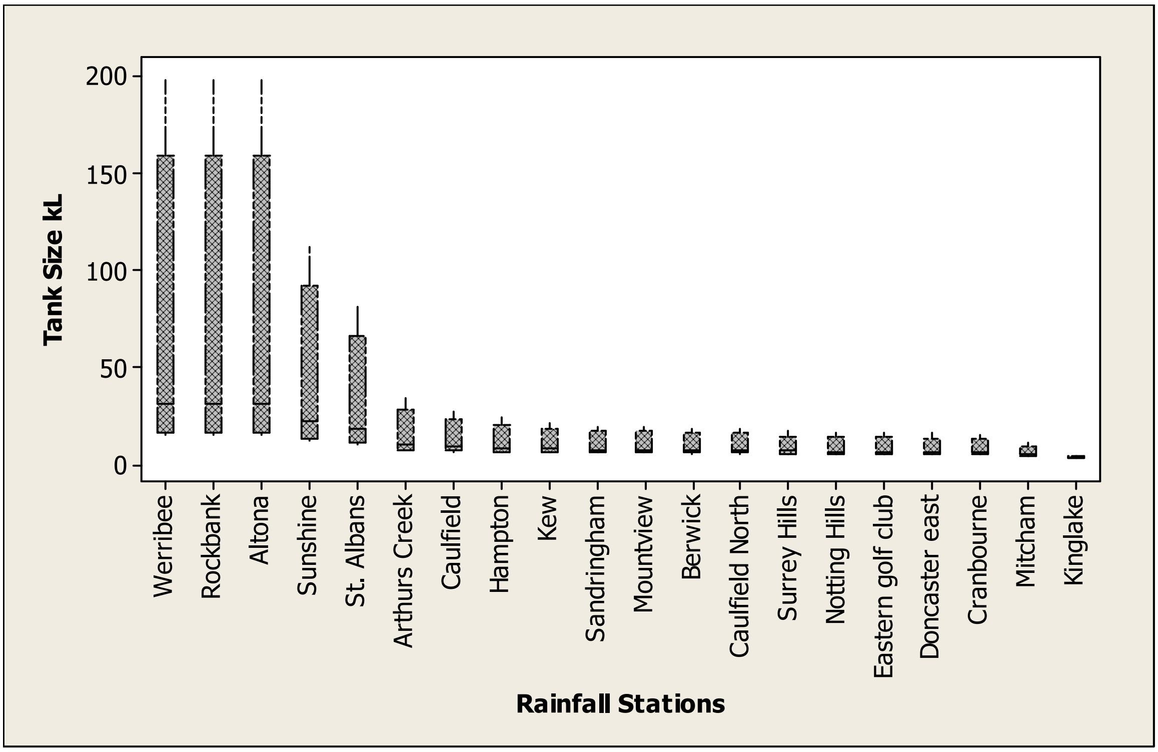

Figure C10 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and toilet and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

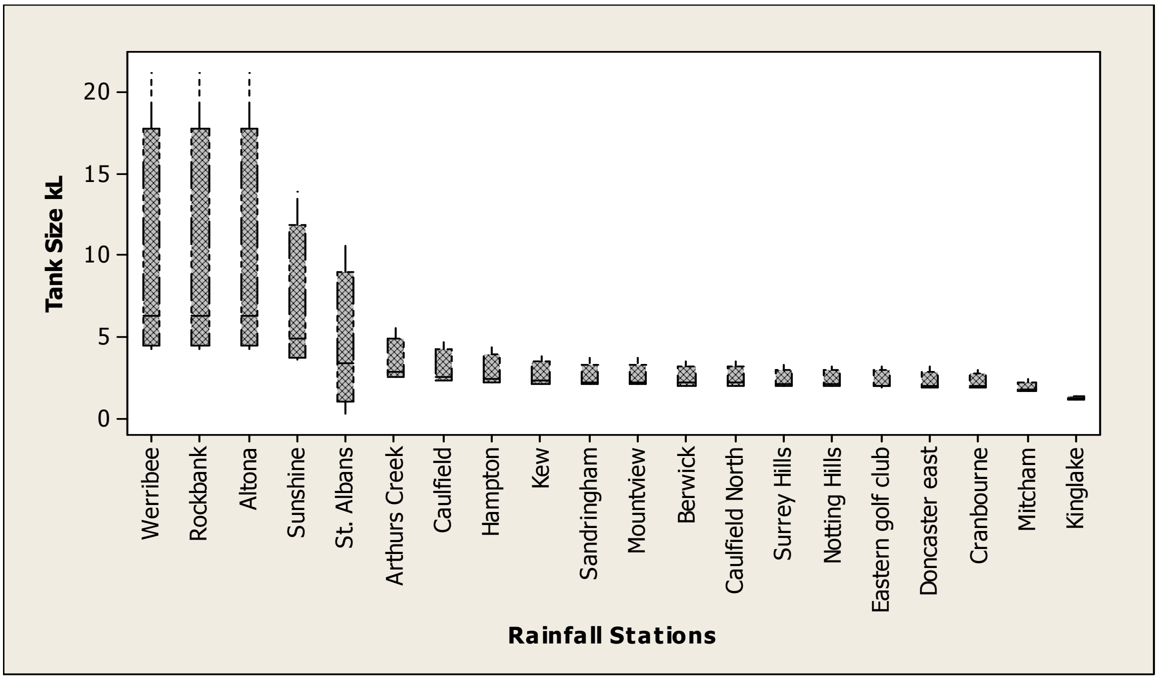

Figure C11 Variation in tank sizes from roof areas at different locations across Melbourne for 90% reliability and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

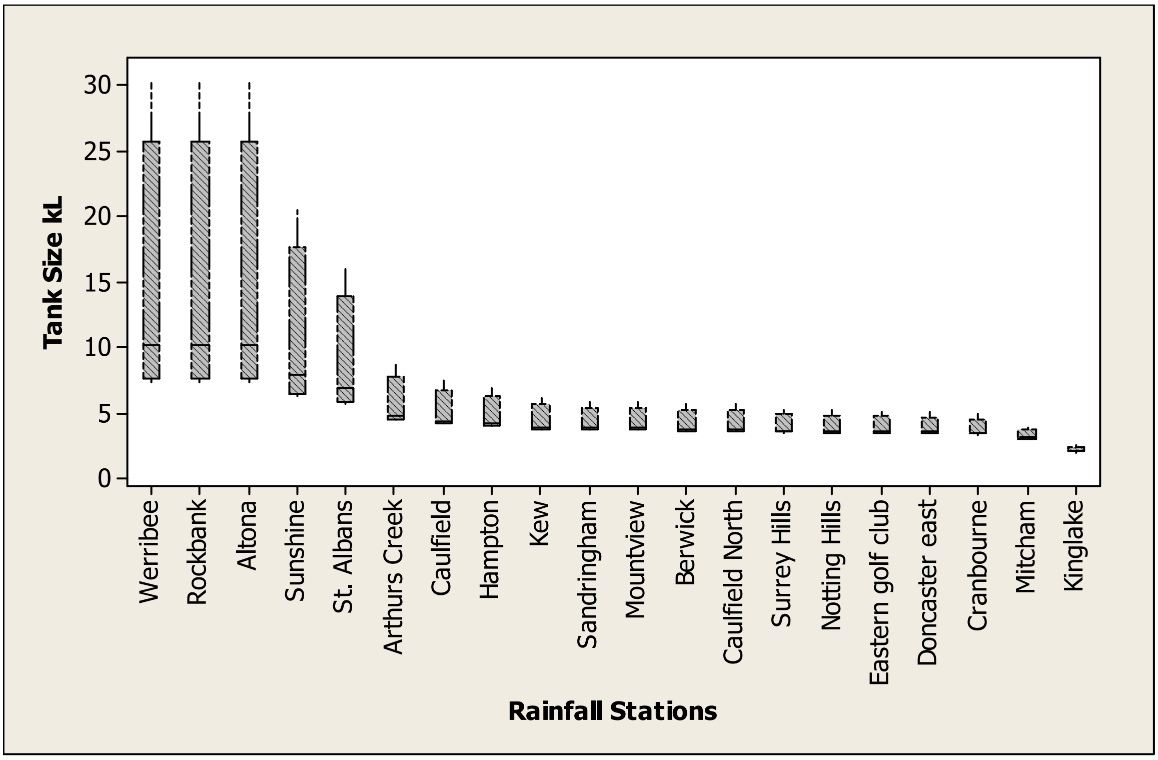

Figure C12 Variation in tank sizes from roof areas at different locations across Melbourne for 95% reliability and toilet, garden and laundry use (lower limit is when A = 250m^2 and upper limit is when A = 100m^2)

APPENDIX D

Water Savings Efficiency for different Water Retail Company Zones

Table D1 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 45645) for the SEW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	61.6	11.2	41.3	22
T+L	67.7	12.0	41.4	22
T+G	92.1	31.3	23.7	13
G+L	74.8	17.0	37.4	20
T	99.8	36.7	17.8	9
L	84.9	17.9	37.2	20
G	98.2	46.2	8.5	5

Table D2 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 56456) for the SEW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	60.2	5.4	39.5	21.4
T+L	66.3	6.1	38.6	21.6
T+G	90.7	25.3	22.7	12.1
G+L	74.1	10.5	36.5	19.6
T	99.9	29.3	17.5	9
L	83.8	11.2	33.9	20
G	97.0	39.5	7.3	4.0

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Table D3 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 64564) for the SEW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	62	7.8	41.6	21.9
T+L	67.8	8	41.7	22.1
T+G	90.6	28.1	23.1	12.1
G+L	75.5	13.2	37.5	19.9
T	98.6	33.8	17.2	9
L	85.5	13.5	37.4	20
G	96.7	43.2	7.9	4

Table D4 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 45645) for the CWW zone

Type of demand	Reliability (%)	Spillage kL/year	Usage kL/year	WSE (%)
T+G+L	43.2	8.9	28.5	15.7
T+L	49.5	9.5	29.5	15.9
T+G	85.4	21.9	21.3	11.8
G+L	59.0	10.6	29.0	16.1
T	98.5	25.3	17.1	9.5
L	68.3	12.0	29.8	16.1
G	96.8	35.2	7.9	4.1

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Table D5 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 56456) for the CWW zone

Type of demand	**Reliability (%)**	**Spillage kL/year**	**Usage kL/year**	**WSE (%)**
T+G+L	42.1	3.7	29.0	15.7
T+L	47.8	4.1	29.0	15.9
T+G	87.5	12.9	22.0	11.8
G+L	58.9	4.6	30.0	16.1
T	99.4	17.7	17.0	9.5
L	67.8	5.0	30.0	16.1
G	97.7	27.1	8.0	4.4

Table D6 Relationship between reliability of supply, spillage, usage and potable water savings efficiency (WSE) for a 3kL tank (Rainfall pattern 64564) for the CWW zone

Type of demand	**Reliability (%)**	**Spillage kL/year**	**Usage kL/year**	**WSE (%)**
T+G+L	42.7	4.9	29.0	15.7
T+L	48.0	5.1	29.0	16.0
T+G	86.9	15.9	21.0	11.5
G+L	60.0	5.8	29.0	16.2
T	99.9	19.9	18.0	9.5
L	68.0	6.4	29.0	16.1
G	97.4	29.3	8.0	4.4

**T = Toilet Flushing, G = Garden watering and L = Laundry use

Appendix E

Published Peer Reviewed Research Papers

Khastagir A, Jayasuriya N "**Parameters influencing the selection of an optimal rainwater tank size: a case study for Melbourne.**" [In CD] Proceedings of the "Rain Water and Urban Design Conference 2007", Sydney Aug 21- Aug 23, 2007

Khastagir A, Jayasuriya N "**Role of Rainwater Tanks in Managing Demand During Droughts**" [In CD] Proceedings of the "Enviro 08 Conference", Melbourne 5 May- 7 May 2008